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Reference guide for building diagnostics equipment and techniques

Charles M. McKenna and Richard H. Munis

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OFFICE OF THE CHIEF OF ENGINEERS

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This report is designed for use by facilities engineers as a guide in the initial phases of investigating building diagnostics equipment and techniques. It provides information related to energy management and building environmental considerations resulting from energy conservation measures. Subjects covered include: 1) building enclosure system evaluation (Chapters 1–4); 2) heating, ventilating and air conditioning (HVAC) system evaluation (Chapters 5–8); 3) lighting/ illuminating system evaluation (Chapter 9); 4) electrical system evaluation (Chapters 6, 8 and 10); and 5) indoor air quality measurements (Chapter 11)

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PREFACE

This report was prepared by the Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire 03755, for the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403, with tri-service funding. The report documents work performed during the period August 1982 to July 1986. Air Force funding was provided via USAF MIPR F82-79, dated 2 August 1982 to CRREL. Navy funding was provided via MIPR N6830582MP20023, dated 20 April 1982 to CRREL. Army funding was provided through Project No. 4A762730AT42, *Design, Construction, and Operations Technology for Cold Regions*; Task C, *Cold Regions Base Support: Maintenance and Operations*; Work Unit 006, *Maintenance and Rehabilitation of Military Facilities in Cold Regions*, in January 1982. The CRREL project manager was Charles M. McKenna.

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A-1

CONTENTS

	Page
Velocity measurements	33
Anemometers	33
Pitot tube	34
Airborne tracers	35
Volume measurements	36
Venturi, nozzle, and orifice flow meters	36
Displacement meters	36
Rotameter	36
Turbine flow meters	37
Positive displacement meters	37
Chapter 6. Energy Metering	39
Energy management objectives	39
Operation and use of energy meters	40
Meter types and their characteristics	40
Chapter 7. Stack Gas Analysis	45
Portable equipment	45
Fixed equipment	45
Chapter 8. Energy Management and Control Systems (EMCS)	47
Chapter 9. Lighting System Evaluation	51
Measurement and analysis	51
Accuracy	51
Advantages	51
Limitations	51
New technology/developments	51
Cost	51
Chapter 10. Electrical System Evaluation—Meters	53
Measurement and analysis	53
Accuracy	53
Advantages/limitations	53
New technology/developments	53
Cost	54
Chapter 11. Indoor Air Quality Measurements	55
Carbon monoxide (CO) monitor	55
Fibrous aerosol monitor	55
Formaldehyde (HCHO) monitors	56
Particulate monitor (active/passive)	56
Particulate sampler/impactor	56
Particulate analyzer	56
Nitrogen dioxide (NO_2) analyzers (active)	57
Nitrogen dioxide (NO_2) analyzers (passive)	57
Ozone meter	57
Radon collector (passive)	57
Radon monitor (active)	58

Page

SUMMARY

Three classes of portable infrared devices can be used for building diagnosis: thermal imagers, spot radiometers, and line scanners. None of these devices used by itself can produce an absolute measurement of temperature, but some devices or systems will produce differential measurements of temperature. Each class and production model of infrared device has certain advantages and limitations. Their uses overlap.

Much of the recent development in thermal imagery has occurred with accessories manufactured specifically for these imagers. Some thermal imagers are multiple-component systems, with a view finder or monitor. Some require cooling. Like all infrared imagers, they work on the principle of converting thermal energy that reaches a sensor into an electrical signal, which is then displayed as shadings of light.

Spot radiometers are cheaper, less sophisticated devices than thermal imagers. A spot radiometer does not produce an image of the surface, and since the area "viewed" by the device increases with the distance from the surface to the instrument, the size of the target at each distance must be calculated.

Only one portable line scanner is manufactured and sold in the United States. There are, however, mounted airborne line scanners also in current use. The unique quality of some portable line scanners is that they feature a composite thermal/visual display that enables the operator to view a scene and obtain an image of that scene with a line of temperature *distribution superimposed on it.*

All portable imaging systems/devices can be used for energy audits, for quality control inspection of insulation installation, and nondestructive detection (but not confirmation) of moisture in walls and built-up roof systems. In most cases, the imagers can be used for interior or exterior inspections, although there are instances in which only one is possible.

Procedures for the use of thermal systems or devices have been and continue to be developed through ASHRAE and ASTM. ASHRAE Standard 101-1981 describes most of the infrared sensing devices currently available from commercial sources and the accompanying procedures. For wood-frame cavity walls, the ASTM-proposed procedure describes the use of thermal imaging devices for quality control inspection of new insulation.

Two techniques other than infrared thermography are used for nondestructive inspection of built-up roofing systems to detect moisture intrusion under the membrane: nuclear meters and capacitance sensors. The nuclear meter requires a grid system to be marked on the roof to identify the measurement location. The capacitance sensor uses either a grid or continuous strip reading to locate moisture. The resolution depends on the fineness of the grid. The number of measurements goes up as the square of grid frequency. Since it is only possible to make measurements at specific locations with these instruments, an inspection will take considerably longer using one of them than with a thermal imager, and some areas of moisture may be overlooked. However, they can be used during daylight hours when operations are considerably less difficult.

In other areas, recent advances in technology have made it possible to automatically measure the air leakage in buildings with tracer gas releases. The three tracer gas methods are dilution, constant concentration, and constant flow. The tracer di-

lution method is versatile and the simplest to use of the three. With the use of air sample bags, tracer dilution does not require highly skilled techniques.

Tracer gas methods are highly dependent upon the weather conditions at the time the tracer is released. Fan pressurization and depressurization can measure building tightness independent of weather conditions, but the larger the building, the more cumbersome the fan method becomes. The fan method can enhance observation of air leakage paths with infrared thermography.

Infrasonic apparatus have been used experimentally for characterizing air leaks in small buildings.

Other air leakage methods employ commercial smoke tracer devices that provide smoke at a well-defined location so a stream of smoke will follow the leakage path, giving visual evidence.

Heat flux transducers (HFTs) are wafer-like sensors that, when placed on building walls or roofs with temperature sensors, can provide a field measurement of R-value. A data acquisition system typically must accumulate differences in temperature and heat fluxes for 48 hours in 40°F (4.5°C) or colder weather.

It is desirable to combine thermal imagery with multiple HFT/temperature measurement to map and quantify the thermal resistance of a building enclosure.

Portable calorimeters are relatively new developments for evaluating the thermal performance of walls. They should be used in conjunction with thermal imagers.

There are many measuring devices used for HVAC system evaluations. These devices measure surface and air temperatures, ambient humidity, air velocity, volume, and pressure. A relatively recent development is the combining of many of these measuring devices into an energy management and control system (EMCS). The EMCS is a centralized energy management system that employs an off-the-shelf mini or microcomputer system. This serves to control functions at multiple locations, for HVAC, lighting, and boiler systems. To control a certain system, the EMCS must be able to monitor various functions. This monitoring can be considered a part of the diagnostic process since it usually provides a display of data that relate to building system performance.

Energy metering is an important part of energy management and control. Many different types of meters are available to measure the flow of liquids, gases, steam, and electricity. The choice of which meters to use and where to locate them depends on how the data will be used and how the energy system is designed.

Stack gas analyzers are available in both portable and fixed types and are useful in maintaining high-efficiency condensation in boilers and furnaces.

Thermal imagers can safely detect hot electrical equipment, such as transformers, insulators, or connections. The chief advantage of a thermal imager is that it can be used remotely and rather quickly to monitor the temperatures of an electrical system without disrupting normal system operation.

One of the most widely used devices for conducting an energy audit of a building's illumination system is the light meter. This device consists of a photocell, appropriate filters, and a meter to register the lighting level. Selenium and cadmium sufide cells are commonly used in a typical light meter. A microcomputer can process the results of a walk-through lighting audit on-site immediately by sending the data over telephone lines to a central computer.

Indoor air quality has recently become a major concern of professionals responsible for the design, operation, and maintenance of large buildings, especially those that are energy efficient. With the introduction of potentially toxic chemical compounds into furnishings, construction materials, and insulation for the residential market, concern has become even more widespread. To obtain some measurement

of indoor air quality to determine maximum acceptable concentration levels of pollutants, a number of both passive and active monitoring devices have been developed. These devices can be used to monitor concentration levels of carbon monoxide, formaldehyde, fibrous aerosols, nitrogen dioxide, ozone, radon, and sulfur dioxide. These measuring devices range widely in cost.

Reference Guide for Building Diagnostics Equipment and Techniques

CHARLES M. MCKENNA AND RICHARD H. MUNIS

INTRODUCTION

The energy crisis of the 1970s fostered a sudden, urgent need for energy conservation measures and, as a result, the field of building diagnostics was greatly stimulated. Traditional building codes had been centered on the health, safety, and welfare of the occupant, but with the rapid upsurge in energy-saving needs, traditional demands were often overlooked. Recently, the urgent need for energy savings has subsided, although conservation needs have not. Often conservation has been accomplished at the expense of occupant welfare, creating a whole new set of problems. As a result, the array of energy-efficiency diagnostic equipment and techniques has been augmented by other equipment for measuring health and safety factors such as air quality, lighting, and noise pollution. This guide is intended to help the facilities engineer provide environmentally sound energy conservation.

There are many ways to effect energy conservation. This guide attempts to present information on diagnostic equipment and techniques that should be generally applicable to all building types. Readers may wish to use the information presented here to better define their problems and to select reasonable solutions. Sections on building enclosures; heating, ventilating, and air conditioning; lighting/illumination; electrical systems; and indoor air quality provide information on the different aspects of energy system diagnostics, which should aid analysis of existing facilities as well as new construction.

Cost figures are in 1986 dollars unless otherwise noted.

Where possible, manufacturers of equipment are listed so that, as the diagnostic approach becomes better defined for the reader's specific application, more detailed information can be obtained than can be presented here. The manufacturers listed for each item give the reader a start in obtaining more information and are not intended to be exhaustive. Readers will eventually develop a more complete file of data applicable to their specific areas of concern.

Chapter 1. Noncontact Temperature Measurement/ Thermal Pattern Recognition

THERMAL IMAGERS

Measurement and analysis

Infrared technology is used to observe and record surface temperature variations. Differences in the thermal resistance or the thermal storage capacity of a building enclosure system (walls, roof) produce variations of temperature over the surfaces, as does the leakage of cold or warm air through the enclosure system. These variations can be located and recorded to determine the position and size of insulation defects, thermal bridges, air leaks, and moisture damage.

Thermal radiation emitted by any object (e.g. building surface) can be used to form an image of that object and to determine its temperature. The amount of radiation from a surface depends on the temperature of that surface and its composition, color, and texture. An infrared radiation sensing device can be used to

- Record an image and measure the temperature of the surface.
- Record only the image of the surface.
- Measure the temperature of the surface.

Infrared sensing devices that image and/or measure surface temperature can determine only relative temperature differences across the surface. If the actual temperature of the complete surface is to be determined, it is necessary first to find the actual temperature at one point on the surface. If that is not possible, then the surface spectral emittance (often available in certain literature) and the calibration data of the infrared device must be known.

Three classes of portable infrared devices are used for building diagnosis: imagers, spot radiometers, and line scanners.

Imagers can be separated into two distinct categories: cooled and uncooled. Both types of imagers can be further divided into

- Multiple-component systems (composed of a separate scanner and monitor) that provide the operator with a thermal image of a surface on a TV-type monitor, and
- A single-component system that must be hand-held to obtain an image of a surface through a viewfinder/monitor provided on the device.

Within these two classes there are imagers that record an image and measure the temperature of the sample and those that display the image of the surface.

All thermal imagers operate on the same basic principle. An optical system transparent to thermal energy focuses this energy onto a sensor that converts it into electrical energy. This electrical signal is processed to produce a display on a monitor in the form of a "heat picture" image of the object on which the infrared device is focused. Depending on the type of imager, the monitor screen displays varying intensities of grays, reds, or greens. In the conventional mode of imager operation, the lighter images depict higher surface temperatures and the darker images, lower surface temperatures. Intermediate tones indicate temperatures between the two extremes.

The image on the screen can be recorded with a Polaroid or 35-mm camera or on video or digital tape. If the image is video-taped, the video image can be photographed. Photographs of heat images are known as thermograms.

Cooled sensors

Two types of cooling techniques are used in single and multiple component imagers: cryogenic and thermoelectric. Liquid nitrogen and high-pressure argon gas are used as cryostat coolants in both multiple- and single-component imaging systems, while thermoelectric coolers (heat pumps) are currently used in only a few systems.

The portable systems that utilize cryogenic cooling have the advantage of drawing only a relatively small amount of power from their batteries; however, this is balanced by the requirement that these systems need Dewar flasks, cylinders, compressors, or other storage and that the sensor cryostats require periodic refilling. Thermoelectric coolers do not require bulky reservoirs or periodic refilling and are so reliable that a failure is usually defined as a loss of a few degrees in cooling over a long time period.

Uncooled sensors

Pyroelectric vidicon systems (thermal television cameras) require no cryogenic cooling. The sensors in these systems respond only to changes in radiance so that radiation from a target must be modulated to produce a thermal image. In lieu of mechanical modulation of the image, panning the camera produces changes in the radiation emanating from a target, which in turn produces an image. A stationary camera also produces an image if there is target movement in the scene.

More important to building diagnostics and preventive maintenance are the types of recording available for documentation. Not all systems can record thermal images on photographs, video, or digital tape.

The techniques by which apparent temperature differences are measured vary somewhat among these systems. The most important point to remember is that no thermal imaging system or device can be used to make an actual temperature measurement of a surface without a reliable radiation calibration source (which produces a reference temperature). This reference temperature can be established through

- A contact measurement of the surface,
- Placement of a reference radiation temperature source in the field of view, or
- A radiation measurement using a calibrated spot radiometer.

The second and third choices above require knowledge of the spectral emittance of the surface.

Whether a measurement of apparent temperature differences or just a documentation of thermal patterns is required, a parameter known as the Miniimum Resolvable Temperature Difference (MRTD) is significant in determining if an infrared sensing device at a critical distance from a target of a certain size can resolve and measure its temperature. The MRTD of any infrared sensing device is established through a standardized measurement procedure. Since not all devices have an established MRTD, a valid comparison among all those in use is not currently possible. However, the difference in inherent image resolution between any two devices, e.g. single-component and multiple-component, can be attributed to the MRTD of each device.

Accuracy

Some imaging systems do not have the capacity for measuring surface temperatures. The data that are obtained with these systems are qualitative and subject to interpretation. The only quantitative data that can be generated by such a system are the percentages of black-white/color contrasts displayed/recorded by the system. For example, a black-white thermal image of an insulated wall shows a certain percentage of that wall characterized by gray tones ranging from black to white. The area of each gray tone can be determined and related to the amount of insulation in the actual wall. It is difficult to specify the accuracy of this procedure because those areas are of various sizes and shapes and are subject to qualitative interpretation. No baseline tests to determine accuracy have been conducted at this time.

It is also difficult to specify an accuracy for those imaging systems that measure surface temperatures. Since almost all infrared systems and sensing devices require an independent reference temperature (e.g. blackbody, contact thermometer) with which to derive a complete and absolute temperature map of a surface, the precision of the measurement depends upon the reference temperature source as well as the infrared system/sensing device and can only be as good as the stated precision of the temperature reference source. The lack of a linear relationship between the electrical output signal of the sensor and the operator marker settings over a wide range of temperatures makes it difficult to specify the accuracy of temperature differences measured with an imaging device. The accuracy of these measurements depends upon the application and the device and can vary from a few percent to approximately 15%.

Advantages

Thermal imagers are noncontact devices used to monitor the temperature of remote surfaces.

Both types of imagers may be operated by one person, and can be either carried or vehicle-mounted. Most imagers can utilize either video or photographic processes. Because of the two-dimensional monitor image presented, identification of the exact target area surveyed is relatively easy. Most imagers also have a fairly large field of view at short distances from the target and will develop an image in real time. Some imagers can quickly measure discrete surface temperature differences. In all, anomalous reflections from a target are relatively easy to discern from real temperature variations of the target.

Some imagers have self-contained systems that need no additional coolant. One of the chief advantages of uncooled detector imagers is that they can be operated in a horizontal or vertical position.

Limitations

An imager used for ground-based surveys cannot easily be adapted for simultaneous display of visual and thermal images. Some systems cannot measure discrete temperature differences. The cost of an imaging system is greater than that of other noncontact radiation-sensing devices. Liquid-cooled imagers require a mirror for vertical viewing. Uncooled imagers require change in or interruption of target radiation.

New technology/developments

The basic technology in cooled detector imaging systems/devices has been evolving during the past 15 years. Much of the development of new technol-

ogy has been associated with accessories that are sold with those systems/devices. Development of new technology for uncooled detector imaging systems/devices has occurred during the past 10 years. One of the most recent developments in uncooled systems/devices is the capacity to measure apparent surface temperatures.

Purchasing information

Cost

Depending upon the characteristics of each of the infrared systems/sensing devices and optional equipment that can be ordered with each the cost will range from $11,000 to approximately $90,000.

Manufacturers

AGA Corp., 550 County Ave., Secaucus, N.J. 07094, (201) 867-5390; Inframetrics, 12 Oak Park Drive, Bedford, Mass. 01730, (617) 275-8990; Hughes Aircraft Co., Industrial Products Div., M/S 514, 6155 El Camino Real, Carlsbad, Calif. 92008, (619) 931-3617; FLIR Systems Inc., 16505 S.W. 72nd Ave., Portland, Ore. 97224, (503) 684-3731.

SPOT RADIOMETERS

Measurement and analysis

A spot radiometer is a relatively light-weight, compact, hand-held device (often manufactured with a pistol grip). A measurement is made by pointing the device at a surface and depressing the on-off switch. The radiometer senses both the radiation from the surface and the reflected radiation from surrounding surfaces. The device incorporates either a temperature-indicating display (meter or digital) in degrees Celsius or Fahrenheit or a radiosity display in Btu/ft^2/hr or W/in.^{2}

A typical range of temperature resolutions for spot radiometers is ±0.1 to 1.5°F with a response time of approximately 2 sec. The target size "viewed" by the device increases with increasing distance from the surface to the instrument (a 3-in. increase for every 4 ft of distance to the target is typical, although this ratio varies for different instruments).

A temperature-indicating spot radiometer is calibrated by pointing it at a reference surface of known temperature and emittance and adjusting the device until it indicates the known temperature of the surface. If the emittance of the test surface is equal to that of the reference surface, the radiometer will be measuring actual temperatures. If a reference surface temperature cannot be determined by other methods, then the instrument operator must estimate the emittance of the surface and set the dial to that value.

Several variations on the basic radiometer design are in current use. The use of microprocessor technology, selectable emissivities, and sighting scopes for defining object size are all found in radiometers used in building diagnostics.

Accuracy

Typical accuracy is ±3% or better.

Advantages

Spot radiometers do not need cooling. They can be used to monitor temperatures in inaccessible locations, thus avoiding dismantling or destructive testing of the building. They are less expensive and more portable than line scanners and imaging systems and, unlike imaging systems, can be calibrated in temperature and radiosity.

Limitations

Since an image is not provided, pinpointing an exact location can be difficult, and although the display is calibrated in degrees, actual temperature is not measured directly. The field view is often limited by the distance from the target, and anomalous reflections from the target are difficult to separate from real temperature variations. In addition, some instruments are sensitive to large ambient temperature fluctuations.

New technology/developments

The most recent developments in the fabrication of spot radiometers include the use of microprocessor technology, state-of-the-art optical and sighting systems, LCD displays, and automatic internal calibration reference.

Purchasing information

Cost

The cost of typical spot radiometers is between $750 and $2000.

Manufacturers

Wahl Instruments, Inc., 5750 Hannum Ave., Culver City, Calif. 90231, (800) 421-2853 or (213) 641-6931; Raytek, 1201 Shaffer Rd., Santa Cruz, Calif. 95060, (800) 227-8074 or (408) 458-1110; Micron Instrument Co., 445 West Main St., Wyckoff, N.J. 07481, (800) 631-0176 or (201) 891-7330.

PORTABLE LINE SCANNERS

Measurement and analysis

A line scanner is a portable infrared scanning instrument that is pointed at a target and allows the operator to see a thermal line scan, which may or may not be superimposed upon a visual image of the target. This line scan represents the temperature distribution along a single line on the target. The composite display enables the operator to locate and analyze thermal characteristics of a target surface. Unlike some scanners, the line scanner sensor operates without cryogenic cooling. A line scanner can be hand-held or tripod-mounted. When records are required, a photographic recording accessory is available. Measurements can be made over various selectable temperature scans. Some thermal imaging systems also include a line scanner capability.

Accuracy

The accuracy of the portable line scanner is difficult to assess for some of the same reasons as for imaging systems.

Advantages

The line scanner can be used to obtain a temperature distribution of the target image on a lineal plane for remote locations. The scanner creates a composite thermal/visual display and the operator views the image of a scene with lines of temperature distribution superimposed. The scanner can be positioned either horizontally or vertically, and the sensor does not need cooling.

Only one photograph of the surface is required for a single-line temperature distribution analysis.

Limitations

Unlike thermal imaging systems, which require one scan of a surface (e.g. building wall), many scans (and a photograph) must be used for line scanners, and actual temperatures cannot be measured directly. Videotape recording is not available with the line scanner. Line scanners are only slightly less costly than two-dimensional imaging systems.

New technology/developments

Currently only one basic type of portable line scanner is being manufactured. No known major technological developments/changes are being made to this device.

Purchasing information

Cost

The cost of portable line scanners is approximately $9,000 to $13,000.

Manufacturers

Pyrometer Instrument Co., Inc., 234 Industrial Parkway, Northvale, N.J. 07647, (201) 768-2000; Wahl Instruments, Inc., 5750 Hannum Ave., Culver City, Calif. 90231, (800) 421-2853 or (213) 641-6931; Mitchel Instrument Co., 1570 Cherokee St., San Marcos, Calif. 92069, (619) 744-2690.

DETAILED PROCEDURE FOR NONCONTACT THERMAL INSPECTIONS

All portable imaging systems have at least one factor in common: they can be used for energy audits, electrical and mechanical inspections, insulation installation inspections, and nondestructive tests to determine the presence of moisture in walls and built-up roof membranes. In each category, however, the system would be used somewhat differently.

Energy audits

Interior inspections

For this procedure a portable imaging system is used to record and document thermal patterns related to air leakage, radiation, conduction, and convection. Evaluation of the thermal imagery is qualitative most of the time, but there have been recent attempts to conduct quantitative analyses.

The objective of an energy audit conducted from the interior of a building is to document and analyze all heat losses from the building enclosure system for the purpose of recommending cost-effective retrofit procedures. Interior energy audits of large buildings can be time-consuming if only one system is used and the complete building enclosure system must be inspected.

ASHRAE draft standard 101-1981 specifies that

> "a thermal imaging system used to assess heat loss characteristics of a building shall provide sufficiently specific and detailed data to permit recognition of the presence or absence of insulation and air infiltration. This category of survey includes three levels of measurement: Class A, Class B and Class C. The Class A survey identifies the probable cause of a heat-loss anomaly, such as distinguishing between insulation voids and air infiltration, as well as providing information to estimate the R-value of the structural component observed. The Class B survey only provides an indication of gross thermal anomalies with limited information on probable cause, while the Class C survey provides for locating gross thermal anomalies with no significant information on probable cause."

According to the ASHRAE standard, the survey must fulfill three basic requirements, depending on the class of survey used:

1. For Class A surveys, the thermal imaging system should provide and document specific data to permit recognition of the probable cause of the heat-loss anomaly, i.e. air infiltration or insulation void. To accomplish this, the imager must resolve anomalies 4 × 4 cm in size or smaller when the temperature difference between the anomaly and its background is equivalent to or less than the interior surface temperature difference between an R-10 and an R-15 surface. Furthermore, the data should be suitable for calculation of the Temperature Index.
2. For Class B surveys, the thermal imaging system should provide and document specific data to permit the location of gross heat-loss anomalies with limited information on probable cause. To accomplish this, the imager must resolve anomalies 16 × 16 cm or smaller when the temperature difference between the anomaly and its background is equivalent to or less than the interior surface temperature difference between an R-5 and an R-15 surface.
3. For Class C surveys, the thermal imaging system should provide and document specific data to permit location of the gross thermal anomalies with no significant information on probable cause. To accomplish this, the imager must resolve anomalies 16 × 16 cm in size or smaller when the temperature difference between the anomaly and its background is equivalent to or less than the interior surface temperature difference between an R-2 and an R-10 surface.

For all survey classes, the thermal imaging system should be capable of producing thermal data on hard-copy records that document the findings for future reference.

The ASHRAE standard specifies that surface and air temperature thermometers, smoke pencils, and air velocity probes may be used in conjunction with the thermal imaging system to record survey conditions. The measurements to be recorded are described in Table 1.

The building's thermal anomalies should be recorded as thermograms, supported by the data necessary to identify the extent of the anomalies within the thermogram. These data may take the form of drawings, photographs, or video tapes. Equipment with photographic capabilities should record such characteristics. For Class A surveys, interior photographs should also be taken to orient characteristics of areas properly within the survey.

Table 1. Recorded measurements

Date
Time of day
Indoor air temperature
Outdoor air temperature
Wind speed
Wind direction
Surface finish and materials
Description of building construction
Window glazing
Surface orientation
Other factors that might affect data

The ASHRAE standard specifies the following survey conditions:

1. A relatively stable condition of heat transfer should prevail.
2. Class A surveys should only be conducted after it is obvious that any solar radiation absorbed during the day has dissipated. This is critical because of the calculation of approximate R-value.
3. Class B and Class C surveys should be conducted only to detect anomalies. They may be performed any time during the day when there is no solar radiation on the walls, as long as the minimum indoor-outdoor temperature differences in Tables 2 and 3 exist for a minimum of 2 hours prior to the survey.

Table 2. Class B survey

Required min. resolvable temp. difference @ 0.13 cycles/cm (°C)	(°F)	*Inside to outside air temp. difference* (°C)	(°F)
0.4	0.7	8	14
0.6	1.1	12	22
0.8	1.4	20	36

Table 3. Class C survey

Required min. resolvable temp. difference @ 0.13 cycles/cm (°C)	(°F)	*Inside to outside air temp. difference* (°C)	(°F)
1.0	1.8	7	13
1.2	2.0	8	14
1.4	2.5	9	16
1.6	3.2	11	20

4. Environmental factors should be noted, including date, time of day, wind speed, precipitation, and site factors such as shading, sun loading, and convective and radiative sources.
5. Approximately 1 hour before the start of the survey, preparation should include elimination of thermal artifacts to the extent practical by turning off heat, moving furniture away from the walls, opening cabinet doors, opening inside doors, drawing curtains to expose the walls, and taking pictures off walls.
6. The equipment designation and serial number should be recorded.
7. Temperature measurements should be made of indoor (Class A only) and outdoor air.
8. Data should be recorded with each thermogram to allow reference to some form of calibrated gray scale to indicate the relationship between contrast and temperature difference.
9. If the survey is used to characterize the apparent thermal resistance, the inside surface temperature of outside walls should be recorded to compute the temperature index.

Within the past two years, the Task Force on Infrared Inspections, Section 7.1, operating under ASTM Subcommittee C16.30, Thermal Measurements, has developed a draft procedure for the thermographic inspection of insulation installations in building enclosure cavities in wood frame buildings. While the procedure has been developed specifically for insulation inspections it could also be used for that part of an energy audit that does not deal with identifiying air leakages. The specifics of this procedure are described below under Quality Control Insulation Inspections.

Interior inspections have certain advantages and limitations depending upon the size and location of the building, time of day, and the meteorological conditions prevailing at the time of the inspection. Inspections of large buildings will require progressively more time. This is the major limitation of an interior survey, but it could be minimized by the use of more than one imaging system and operator.

The advantages are that: solar loading of the exterior surface of the building enclosure does not bring an immediate end to the survey, wind scrubbing of the exterior does not have a direct effect on the degradation of the thermal image, and meteorological conditions (precipitation, temperature, wind chill) do not reduce the productivity of the imaging system operator. In addition, natural barriers (e.g. trees, shrubs, water, steep slopes) do not interfere with the operator's mobility.

Qualitative pattern recognition analysis of thermal images has been and will continue to be the primary means of providing data for audits of both residential and nonresidential buildings. Recently there has been a trend in the development of procedures to obtain actual temperatures from those imaging systems that have that potential. While most of this effort is in the primary stage, it is anticipated that within the next few years enough progress will have been made to consider the measurement of actual surface temperatures of buildings as routine.

Exterior inspections

Most exterior surveys of buildings using imagers are conducted with hand-held devices or cart-mounted systems. With the rapid advance of technology, many diagnosticians are using direct video data-recording techniques while others are using photographic records or simply written notes based on thermal data and visual observations.

In the past, diagnosticians considered the best temperature conditions to be satisfied with an as-large-as-possible temperature difference between inside and outside. Such conditions imply that the outside temperature should be very low while the inside temperature remains at ambient. Recent tests by Public Works Canada of the minimum resolvable temperature difference of various imaging systems indicate that detectors used in these systems become less sensitive as the ambient temperature is decreased from 59 to –22°F (+15 to –30°C). The minimum temperature difference considered to be acceptable for exterior surveys depends upon whether a high- or low-resolution imager is being used. If a high-resolution system is used, a temperature difference of approximately 14.5 to 18°F (8 to 10°C) is required for observable contrast in the thermal image. A low-resolution imager usually requires an 18 to 27°F (10 to 15°C) temperature difference for an observable contrast.

A compromise must be made between the spatial and thermal resolution of the imaging system and the time required to complete the survey. An attempt should be made to include as much as possible of the exterior surface of the enclosure system without violating the minimum resolvable temperature difference specifications of the particular system being used.

The sensitivity of the imaging system should be adjusted to give the lowest minimum resolvable temperature difference that keeps the image from being saturated to black or white. The thermal image from the screen can then be recorded manually, photographically, or with video tape. To indi-

cate the relationship between contrast and temperature differences, data should be recorded to allow reference to a calibrated gray scale or to two surface reference measurements.

One distinct advantage of an exterior survey of a large building is that it can be conducted in much less time than an interior survey. Where time is of the essence and only one imaging system is available, an exterior survey can be conducted to identify and document quickly most thermal anomalies within the building enclosure system.

Another advantage is that objects (furniture, etc.) behind the walls of the building enclosure system do not have to be moved as long as there is recognition of those objects at the time of the survey.

One disadvantage of an exterior survey is the problem of solar loading of the building enclosure system. Only a few minutes after the sun hits the building, heat is absorbed and an imager can no longer distinguish between the incident solar radiation and the outgoing thermal radiation. Therefore, an exterior survey should be made at times of minimum solar heating of the enclosure system. If the enclosure system has already been heated, then for walls it is usually necessary to wait for at least 3 hours after sunset to avoid solar storage affecting the solar decay (or build-up) process before the diagnostic survey is begun. For roofs, 2 hours after sunset in the summer and 1 hour in the winter is usually an adequate waiting time.

Another disadvantage is the problem of wind scrubbing of the building surface. The wind reduces the overall thermal image contrast by eliminating the surface temperature differences that depict thermal anomalies in the building enclosure system. At the present time there is no general agreement as to what value of wind velocity is considered excessive for observable image contrast. Even though ASHRAE Standard 101-1981 indicates that this phenomenon is wavelength-dependent and limiting at wind velocities over 15 mi/hr (24 km/hr), Public Works Canada has documented instances of observable thermal image contrast obtained with wind velocities exceeding 15 mi/hr.

Exterior surveys are also hindered by the environment immediately adjacent to a building (e.g. trees, shrubs, fences, water, other structures, sloping landscapes). Any of these objects may be located in such a manner as to hinder the mobility of the equipment operator or prevent him or her from getting an unobstructed view of section(s) of the building enclosure system.

Public Works Canada has used a helicopter to conduct exterior surveys of large multistorey buildings. It is used in conjunction with a thermal imaging system coupled to an optical system that produces a thermal image superimposed on a visual image. This technique has the distinct advantage of being able to provide a correlation between thermal anomalies observed in the thermal image and the precise location of those anomalies on the building enclosure system.

QUALITY CONTROL INSULATION INSPECTIONS—INTERIOR AND EXTERIOR

Most of the procedures for conducting a quality control inspection are described in Chapter 6, Energy Metering. The procedures are identical for energy audits and quality control inspections with regard to determining whether a new or retrofit insulation installation is done according to specifications, job contract, proposals, standard installation practice, or applicable codes and standards. Other thermal anomalies that are observed during the process of an energy audit may require procedures not covered in a quality control inspection. The Task Force on Infrared Inspections, Section 7.1, operating under ASTM Subcommittee C16.30, has prepared a draft "Practice on Thermographic Inspection of Insulation Installations in Envelope Cavities in Wood Frame Buildings" that specifies procedures that are applicable to inspections of quality control insulation installations. Unlike ASHRAE Standard 101-1981, the ASTM-proposed practice deals with the operator's level of knowledge. It states that "a trained thermographic operator and data evaluator shall have knowledge and competence in principles of infrared theory, air movement, moisture migration, heat transfer, and a basic understanding of building enclosure theory in order to apply techniques to diagnose defects in building envelope systems."

According to the proposed practice the following environmental conditions are preferred for thermographic inspections:

- Minimum temperature difference of 10°C between interior and exterior ambient for a period of 8 hours prior to the inspection.
- No direct solar radiation on the surfaces for the previous 3 hours for wood frame with siding and the previous 8 hours for masonry and masonry veneer construction.
- For exterior surveys, wind speed should be less than 15 mi/hr (24 km/hr) and the wall should not be wet.

Although it is recommended that the above conditions prevail at the time of inspections, it is recog-

nized that inspections can be performed under other conditions if sufficient knowledge is used in taking and interpreting the thermal images. For example, a wall exposed to direct solar radiation will experience a temperature reversal—the studs and voids will appear warm and the insulated section cold on interior inspections. An exterior inspection will show the studs warmer than the insulated sections.

On many veneer surfaces, interior surveys are technically possible 1 or 2 hours after sunrise.

The proposed practice states that, to evaluate the structure for installation of insulation, certain preliminary data should be collected, if possible:

1. A sketch or record of each type of anticipated wall cross section, noting the age of the construction, i.e. construction drawings and anticipated thermal pattern.
2. Additions or modifications to the structure.
3. Locations that the insulation contractor was contracted to insulate, the type of insulation (if known), and the anticipated R-value.
4. Difficulties encountered by the insulation contractor.
5. Thermal anomalies noted by the owner/occupant.
6. Type(s) of existing insulation(s).
7. Type(s) of exterior and interior surface finishing materials that might produce unwanted reflections.
8. Orientation of exterior walls.
9. Potential paths of air leakage into cavities.
10. Extraneous heat sources mounted on or close to the walls.
11. Time the building is used.

With regard to information on the outdoor environment, the practice states that the meteorological conditions that prevail during the inspection can greatly affect the thermal image. In conducting an inspection, the following locally measured interior and exterior environmental conditions should be recorded:

1. Exterior ambient temperature (on site).
2. Wind speed.
3. Wind direction.
4. Cloudiness.
5. Relative humidity.
6. Precipitation for the previous 12 hours.
7. Maximum and minimum exterior ambient temperatures for the 24-hour period prior to the inspection.
8. Cloud-cover estimates for a period of 12 hours prior to the inspection.

Inside the building, the air temperature should be measured in each room on each level and in the basement to an accuracy of 1°F or 0.5°C. Relative humidity should also be recorded for each level of the house. Unheated spaces should be noted and the interior temperature recorded. If certain rooms have temperatures differing by more than 4°F or 2°C from the temperature of the corresponding rooms on another level, those temperatures should be reported.

As mentioned in a previous section, not all surfaces are accessible for inspection from the exterior and interior. Ideally, all movable obstacles blocking the view of the surface should be moved, and if they are in contact with the surface, they should be moved at least 1 hour before inspection.

The heating system should be left off unless turning it off will cause more than a 4°F or 2°C change in temperature. Operation of the heating system could mask existing thermal anomalies. In contrast with the ASHRAE standard, the proposed ASTM practice is specific with regard to on-site equipment check and settings:

1. Verify that the system meets MRTD requirements for the temperature gradient through the wall.
2. Instrument gain or contrast should be set to allow the operator to distinguish a stud in the image from the wall around it. The brightness or level control should be set so that anomalies or their reference areas are not in saturation (maximum brightness or white) or in suppression (minimum brightness or black) on the display.
3. Verify proper operation of the recording system (if any).
4. Produce a hard copy of the thermal image of the wall.

Similarly, the specifics of the inspection are outlined in the ASTM practice:

1. A complete quality control inspection of the building may consist of both an exterior and interior inspection of all surfaces that should have been insulated.
2. Inspections should be made of all surfaces that can be viewed with an angle of less than 30° from normal to the surface. Inspections should be made from several angles to detect the presence of reflected radiation.
3. For an interior inspection, scans should be made from a position that allows a view of at least two horizontal and one vertical stud space.
4. For an exterior inspection, scans should be made from a position that allows a view of at least six horizontal and three vertical stud spaces.
5. Hard copies of each anomaly with a notation of the location of all building characteristics

(e.g. windows, doors, and vents) should be made. The quality of the hard copy should be based on the need for calculations of areas with insufficient insulation or for identification of cavities with varied defects.

The primary purpose of the quality control inspection is to provide precise physical location information to allow for corrective retrofit.

It is not possible to provide a detailed interpretation of thermal patterns without some understanding of the construction of the building. If there are air spaces between the inspected surface and the insulation, it should be determined whether there are heat sources in the cavity and the composition of the wall enclosing the cavity. In comparison with the studs, locations without insulation appear colder in interior inspections and warmer in exterior inspections. Air leakage between the insulation and the surface may cause a thermal pattern similar to a location without insulation. The interpretation of the thermal image or other hard copy allows determination of the following:

- Total area and location where there is no insulation.
- Total area and location where there is full insulation.
- Total area and location where there is only existing insulation (for those applications where insulation is being added).
- Location of cavities with improperly fitted insulation, or shrinkage.
- Location and extent of air leakage or moisture damage.

Irregularities in the insulation and air tightness of a building will provide various apparent surface temperature patterns. Certain types of defects have characteristic shapes in a thermal image. In evaluating thermal patterns, the following characteristics are considered:

- Relative uniformity of the thermal pattern.
- Contours and characteristic shapes of the thermal patterns.
- Irregular pattern shapes with uneven boundaries and large temperature variations produced by air leakage in the building enclosure.
- Regular and well-defined pattern shapes produced by missing insulation.
- Mottled and diffused patterns produced by moisture in the structure where temperature variations are not extreme within the pattern.
- Measured difference between the temperature at a location on the wall with full insulation and the temperature of the selected colder or warmer region.
- Continuity and uniformity of the constant temperature region over the surface.

The type of defect can usually be determined by calculations, ancillary measurements, experience, or by comparing the actual thermal image with reference thermal images for structures with known insulation defects. Such determinations should be substantiated in the report.

The ASTM practice specifies that the report on a quality control inspection should contain, at a minimum, the items listed below:

1. A brief description of the construction features of the building. (This information should be based on drawings or other construction documents when available.)
2. The types of surface materials used and their estimated spectral band emittance.
3. The orientation of the building with respect to the points of the compass and a description of the surrounding buildings, vegetation, landscape, and microclimate.
4. Equipment specifications, including model and serial number and any critical settings used during the measurement.
5. The date and hour of the inspection.
6. Outside air temperatures observed in the course of the 24 hours before and during the inspection.
7. Information about the solar radiation observed in the course of the 12 hours before and during the inspection.
8. Precipitation, direction, and velocity of the wind during the inspection.
9. Inside air temperature and air temperature drop across the enclosure.
10. Any other important factor influencing the results.
11. Sketches/photographs of the building showing the positions of the thermal images.
12. Thermal images with indications of their respective positions, and with comments on their appearance.
13. Results of the analysis dealing with the type and extent of each defect that has been observed.
14. Results of supplementary measurements and inspections.
15. Estimate of the total area and location where there is no insulation.
16. Estimate of the total area and location where there is full insulation.
17. Estimate of the total area and location where there is only existing insulation (for those applications where insulation is being added).

18. Names of members of the inspection team and the team leader.

NONDESTRUCTIVE SUBSURFACE MOISTURE TESTS

Thermal imagers

Using visual means to detect moisture within the insulation of built-up roofing systems and then cutting into the membrane for verification has provided a useful but localized view of moisture-damaged roofs. Experience has indicated that this procedure often leads to misinterpretation of roofing problems.

The development of roof inspection techniques that use thermal imagers has provided a means of quickly detecting and accurately mapping subsurface roof moisture and plays a significant role in nondestructive testing of roof assemblies. Due to the portability of imaging equipment, surveys can be performed by walking the roof or by scanning from the air. The method selected depends on the construction of the roof assembly, climatic conditions, the size of the roof, the number of roofs being surveyed, the problems, and the information desired. The best time to survey a roof is during the night. Certain problems can also be investigated from the interior, and good results have been obtained using this technique with adverse weather conditions. Information can be stored on video tape or film, depending on the future use of the information.

Although wet insulation is usually depicted as a bright area on the viewing screen of a thermal imager, not all brightness can be attributed to entrapped moisture. Exhaust from roof-mounted fans or heaters suspended below the roof, changes in construction, and repairs on areas that have been reroofed often resemble entrapped moisture on the thermal image.

The technique of thermal imaging senses variations in surface temperature and only senses the effect of moisture as it relates to the surface temperature of the membrane. All materials between the interior and exterior of a building, including the ceiling and air spaces, are considered part of the roof assembly, and all influence the thermal performance of the roof.

Moisture reduces the insulation's effectiveness and increases its conductivity. At night, during cool or cold months, this moisture can be depicted in a thermal image as warm zones on the roof's surface.

During warm or hot months, under conditions of intense solar radiation, the roof acts as a large thermal collector. Any insulation laden with moisture absorbs this radiation and acts as a heat sink. After sunset, especially on a clear night when there is good radiant cooling of the surface, the moist areas tend to hold their heat, forming warm zones. The amount of thermal energy stored by a roof is directly related to its construction and the volume of moisture trapped within it.

The period in which the inspection must be done begins after sunset when the wet insulation areas remain or become warmer than the dry areas, providing a detectable temperature differential. As the roof cools through the night, the temperatures of the wet and dry insulation areas tend to equalize.

During the inspection, thermal anomalies may appear. Because these anomalies may be associated with phenomena other than wet insulation (e.g. interior heat sources, light fixtures, steam pipes, heavy gravel, etc.), they must be verified by taking roof cores or by other means.

The use of thermal imagers for mapping subsurface roof moisture has one very significant advantage. Since these imagers can be used to quickly pinpoint the presence of subsurface moisture in insulated roof systems, only those locations that are suspect need be considered for maintenance action. This means that the "guesswork" of attempting to locate suspect subsurface moisture over large roof areas has been virtually eliminated from the process of visual inspections. Once moisture has been confirmed in the suspect locations, the cost of reroofing will be limited to those specific areas. Before the advent of the use of thermal imaging techniques there was no way to quickly "see" the presence of subsurface moisture. Now that these techniques are readily available it is possible to quickly and precisely assess where maintenance action is required. The potential annual cost savings with this diagnostic technique can be enormous.

There are several limitations to the use of thermal imagers for roof subsurface moisture inspections. Proper interpretation of the thermal requires a thorough understanding of both infrared theory/applications and roof construction. The equipment must be capable of detecting relatively small temperature differentials that may occur with damp insulation or under less than optimal conditions. It must render an image with sufficient clarity and contrast to provide useful and readable information throughout the entire inspection period. The imager must be portable enough to permit the operator's access to all areas of the roof to be in-

spected. Uninsulated roofs do not, in general, retain sufficient quantities of moisture for a long enough time to permit infrared inspections.

Environmental conditions must be near optimal to locate interply moisture. Since felt plies are highly porous, interply moisture is a transitory state and may be more readily and economically located by visual examination. Therefore, the use of instrumented inspection to locate interply moisture is of questionable value.

Lightweight concrete decks may be inspected, but care must be used in interpreting the data. These systems are poured in place and often retain a significant moisture content, so the data may appear to indicate unacceptable moisture contents throughout the entire roof. Inspections of this type of system are more difficult because the boundaries of the wet areas are indistinct and extensive verification is necessary.

Thick layers of insulation may mask the thermal loading effect on moisture retained in the lower layers and prevent its accurate location. Any thermal insulator placed over a layer of wet insulation makes moisture detection more difficult.

An aluminized surface reduces the energy reradiated from the roof and increases the energy due to reflectance. Therefore, it may be impossible to inspect a newly aluminized roof surface until the surface reflections have been reduced through oxidation or other contamination.

A surface with heavy gravel above the insulation will retain sufficient heat to prevent the detection of temperature differentials due to the moisture content of the insulation, making it difficult if not impossible to survey. Anything on the building interior or exterior that significantly affects the roof surface temperature may make accurate inspection results impossible to obtain.

When a roof inspection depends upon temperature differentials generated by solar radiation, a roof shadowed by clouds, trees, or building appurtenances may not receive sufficient solar energy to permit an inspection. The roof must be free from surface moisture or snow during the inspection. If the roof surface is wet the day of the inspection, the sun's energy will be spent drying the surface instead of warming the wet insulation. Inspection of the surface may be difficult.

Winds in excess of 15 mi/hr (24 km/hr) will significantly increase the convective cooling effect on a roof and will cause the wet and dry areas to rapidly reach the same temperature. This effect shortens the time of inspection.

Although an infrared inspection of a roof is generally regarded as a nondestructive test, verification of the results may not be. Since thermal image interpretation cannot absolutely guarantee the presence of subsurface moisture, other means of verification must be used. Roof cuts are the most reliable. The use of thermal imaging techniques must be considered quasi-nondestructive until such time as a nondestructive verification technique is developed.

The use of thermal imaging techniques for subsurface moisture inspections of roofs is a recent development. There have been no known recent significant advances in inspection techniques.

Spot radiometers

Theoretically a spot radiometer can be used in every application in which an imaging system is used, but from a practical perspective it would be difficult to justify its substitution in every instance because of the basic and significant difference in the characteristics of each device. Due to the localized measuring capability of the spot radiometer, ASHRAE Standard 101-1981 recommends that it be used for (1) interior measurements of wall segments to detect the presence of thermal anomalies and (2) to determine the apparent range of thermal resistance of a building component utilizing the Temperature Index or similar technique. The standard does not recommend the use of the spot radiometer for exclusive use in conducting surveys of total wall sections or for complete building surveys for identifying all insulation voids and air leakage paths.

The ASHRAE standard has established two classes of interior measurements. The Class A measurement is used to locate the presence of thermal anomalies and to determine the local range of apparent thermal resistance (R-value) of a building component, while the Class B measurement is used only to detect the presence of thermal anomalies.

For Class A measurements, the standard stipulates that:

- A spot radiometer be calibrated with a blackbody reference with a temperature accuracy within ±0.5°F (0.3°C).
- Indoor ambient and outdoor air temperature be determined within an accuracy of ±0.5°F (0.3°C).
- Outdoor air temperature be measured with a conventional thermometer.
- Indoor ambient temperature be measured with a spot radiometer by pointing it at an object that has an emittance similar to the exterior wall and thermally insulated from it.
- Spot checks to determine the range of apparent thermal resistance be conducted no sooner than 3 hours after sunset.

- The heating system be turned off 1 hour before measurement.
- Curtains and drapes be pulled closed.
- Measurements not be made on reflective surfaces.

For Class B measurements, the standard states that:

- The indoor/outdoor ambient air temperature difference must exceed the appropriate value for a period of at least 2 hours before any measurement.
- Spot checks in no case should be made when the indoor/outdoor air temperature difference is less than 18°F (10°C).
- Exterior to interior surface measurements of building components exposed to solar loading must exceed the appropriate values.
- The heating system must be turned off 1 hour before measurement.

In actual use the spot radiometer is panned across a wall section slowly to allow for the instrument response time. Any significant temperature changes are noted by the operator.

The following data are recorded:

Date
Time of day
Indoor ambient temperature
Outdoor air temperature
Wind speed
Wind direction
Weather conditions
Surface finish and materials
Description of building construction
Window glazing
Surface orientation
Other factors that might affect data
Range of apparent thermal resistance
Apparent outdoor/indoor temperature difference.

When making Class A measurements using the temperature index method,the range of apparent thermal resistance is determined using the procedure given in Section 3 of the appendix of the ASHRAE standard. When spot checks are conducted to determine the existence of cavity insulation, certain criteria are applied to determine if in fact that insulation is present: the wall is insulated if the apparent surface temperature between studs is greater than the apparent temperature of the studs and uninsulated if the apparent stud temperature is less.

Virtually all of the same advantages and limitations of interior and exterior inspections are experienced by operators of spot radiometers and imaging systems. The additional limitations of a spot radiometer (nonimaging and nonscanning) create additional problems for the operator, however. One problem is the increased time required to conduct a complete energy audit, quality control insulation installation inspection, or electrical/mechanical inspection. The other problem is the rapidly expanding field of view that occurs with increasing distance from the surface being measured without benefit of an image that can be monitored. Without the benefit of an imaging capability, it would be almost impossible to use a spot radiometer in any application requiring pattern recognition (e.g. subsurface moisture tests of roofs and walls). Therefore, its use must be restricted to those applications that require extremely localized surface temperature measurements.

The advantage of using a spot radiometer is that for extremely localized surface temperature measurements, it can be used to quickly measure them and infer a range of R-values for that particular locale.

Portable line scanners

The use of portable line scanners is not unlike that of a thermal imaging system. The significant difference is that an imaging system automatically produces a thermal image of an object through a combination of optical and electronic components, while a portable line scanner produces a surface temperature profile superimposed on a visual image. A complete temperature map of a surface can only be made by manually scanning (moving the scanner up or down to produce temperature "lines" that are superimposed on the visual image of the surface being observed).

At the time the ASHRAE standard was being drafted, no portable line scanners were being sold, so the standard does not cover the use of such a device.

Because the line scanner is not an imaging device, the time limitations for large-scale surveying would be similar to the limitations of a spot radiometer. However, because a visual image can be produced, use of the line scanner generally has the advantage of taking less time to correlate a thermal anomaly (once it is located) with its precise physical location.

For certain applications of electrical inspection, a portable line scanner has the advantage of not being affected by spurious electromagnetic fields produced by the electrical equipment itself. This means that if the components to be inspected are obstructed by other components, objects, or equipment, an operator can move in close with the line scanner to get an unobstructed view.

Chapter 2. Noncontact Electromagnetic Measurements

NUCLEAR METER

Measurement and analysis

As early as 1941, a paper in *Oil and Gas Journal* described the basic process used in the nuclear meter. The instrument was developed for use in petroleum exploration and consisted of a neutron source and an ionization chamber.

The nuclear method for determining the moisture content of a material is based on the principle of measuring the slowing of neutrons emitted into the material from a fast-neutron source. The collision of the fast neutrons with hydrogen atoms in the material slows those neutrons. The number of slow neutrons is detected by a counter tube and electronically counted. The slow neutron count is proportional to the amount of water in the material.

The nuclear meter has been used successfully to delineate entrapped moisture on a large number of built-up roofs. The meter is reasonably simple to use, requiring only the meter and a calibration block. The work can be done by two people who are trained in the use of the instrument. An average of 400 readings (approximatelv 32,500 ft^2 or 3020 m^2 of roof area) can be surveyed per day.

Accuracy

The accuracy of the nuclear meter has not been determined for roof measurements.

Advantages

Nuclear meters can be used to detect entrapped roof moisture. The number of backscattered slow neutrons received (compared to a reference standard) is directly related to the number of hydrogen atoms present in the entire roof cross section under the meter from the surface to the deck. A reference grid system provides an accurate location of entrapped moisture at the expense of increasing the time required to complete the job. The nuclear meter can also be used to check out and verify suspect locations found with an infrared scanner. Use of a nuclear meter provides contact with the roof during daylight hours, when visual inspection of the roof materials can be made.

Limitations

The means of detecting entrapped moisture is direct in that the meter responds to hydrogen ion concentrations in the material. A grid system must be laid on the roof and readings must be made at each grid intersection. This procedure slows down the survey, but provides an accurate map, since each reading is referenced to a position on the roof surface.

New technology/developments

None.

Purchasing information

Cost

The instrument costs from $2800 to $5500 and can be used for several years without extensive maintenance.

Manufacturers

Campbell Pacific Nuclear, 130 South Buchanan Circle, Pacheco, Calif. 94553, (415) 228-9770; Seaman Nuclear Corp., 3846 W. Wisconsin Ave., Milwaukee, Wisc. 53208, (414) 762-5100; Troxler Electronic Labs, Inc., P.O. Box 12057, Cornwallis Rd., Research Triangle Park, N.C. 27709, (919) 549-8661.

CAPACITANCE SENSOR

Measurement and analysis

The dielectric constant for a roof containing moisture is significantly different than for a dry roof. For example, water has a dielectric constant of about 80, while dry roofing materials have a dielectric constant of approximately 4. This extreme difference enables the use of an electronic capacitance sensor to detect moisture in both insulation and membrane.

Moisture readings taken from the capacitance system are plotted on a drawing of the roof to create a three-dimensional representation of moisture content.

Accuracy

Information on the accuracy of the capacitance sensor is not available.

Advantages

The sensor can detect moisture in both membrane and insulation.

Limitations

The sensors cannot give quantitative results. A grid has to be laid on the roof, increasing survey time.

New technology/developments

None.

Purchasing information

Cost

$275 to $4200.

Manufacturers

A-Tech, P.O. Box 5576, Madison, Wisc. 53705, (608) 831-5333; Tramex/United, 1300 Shoshone St., P.O. Box 4246, Denver, Colo. 80204, (303) 892-0400.

Chapter 3. Contact Heat Flow Measurements

HEAT FLUX TRANSDUCERS

Measurement and analysis

A heat flux transducer (HFT) is a thin wafer, either circular or rectangular in shape. The wafer contains an embedded thermopile (a series of pairs of thermocouple junctions placed across the wafer), which produces a signal proportional to the rate of heat flow passing through the wafer.

The constant that relates the output to the heat flow rate is called the sensitivity of the device (expressed in millivolts per Btu/(hr/ft^2)), which is a slight function of its average temperature.

ASTM (1985a) specifies the procedure outlined here more fully; see also ASTM (1985b) and Flanders (1987).

The output signals from heat flow sensors can be read out at any interval using data loggers, strip-chart recorders, or analog integrators. Any readout device must have sufficient sensitivity to resolve a signal at its lowest level.

Manufacturer's calibrations of HFTs are seldom valid for use on buildings. Because HFTs distort the heat flow they are intended to measure, a change of materials, temperatures, or other factors may change the conversion factor significantly. Calibration of HFTs should therefore duplicate the material and thermal surroundings in which they are to be used. If the sensor is to be permanently embedded in the construction, then the calibration should represent the materials on either side of the sensor. If the HFT is to be surface-mounted, then the calibration must occur in an apparatus that simulates this. In either case, the temperatures and heat flux during calibration should approximate the average temperature and heat flux that the sensor is likely to encounter. ASTM (1985b) describes these requirements in greater detail.

When HFTs and thermocouples are to be surface-mounted, masking tape usually provides good attachment, smoothes over the sensor to avoid disrupting air movement, and provides adequate matching of infrared absorptivity. The match of absorptivity is important so that the sensor will absorb heat in a manner similar to its surroundings. Surface-mounted HFTs should be on indoor surfaces only because they are strongly influenced by solar radiation. Curtains should be drawn to prevent the sun from shining on measured surfaces. Gaps of more than 0.5 mm (0.02 in.) between the HFT and the surface can cause errors from 2 to 10% because of convection. A layer of gel toothpaste or similar substance behind the HFT can improve thermal contact. Thermocouple leads should be attached to the surface for a foot or so behind the junction to ensure that the measurement represents the surface temperature.

Thermocouple junctions are mounted under masking tape to the inside and outside surface of the building component. The junctions should ideally be covered with the same paint that was used on the wall, to match the absorptance and emittance of the measuring location with that of the surface, but masking tape usually provides an adequate match. Thermocouple leads should be run at least a couple of feet along the surface to minimize heat conductance along them.

Accuracy

When the HFT technique has been used in field and laboratory studies to determine the thermal resistance of walls and roofs and when the composition of the wall was known accurately, the agreement between measured thermal resistance and the corresponding predicted thermal resistance using steady-state heat transfer theory has agreed to within 6%. For the calculated values, heat transfer coefficients from engineering handbooks are used. Without a third means of verification, such as drilling an inspection hole, it cannot always be determined whether the difference between measurement and theory is due to the use of incorrect values of the material properties or to inaccuracies associated with the measurement.

Advantages

In attempting to assess the thermal performance of building components, it is necessary to determine the quantity of heat passing through that component in a given period of time. The result of this measurement, together with interior/exterior surface temperature data taken over a period of time, can be used to calculate the thermal resistance (R-value) of the component.

An HFT produces a quantitative value.

The most important advantage of using HFTs for measurement and analysis is that they produce a signal output that is related to the heat flow through that particular location. The addition of contact temperature sensors to the inside and out-

side surfaces allows the thermal resistance (R-value) of the building component at those specific locations to be calculated.

Limitations

Since an HFT is a contact transducer, it must be mounted securely to ensure the accuracy of the measurements. Thermography is recommended to assure that sensor sites are appropriate. Once the sensor is placed, the results obtained are only applicable to that one spot.

An HFT with a relatively small thickness can have a fluctuating signal. This may require averaging.

Since the sensor contacts the surface, heat flow at that location is perturbed. If the heat flow is only in one dimension (i.e. through the surface), the sensor should be measuring the actual flow rate. However, if the heat flow is multidimensional (i.e. along and through the surface), the sensor will not be measuring the actual flow rate.

It takes approximately 2 hours to set up 20 heat-flow sensors (HFTs).

Since careful calibration, detailed measurement preparation, and proper data interpretation are necessary, qualified technicians are needed to carry out this procedure. Field personnel should be experienced with proper low-level electrical measurement techniques and should also have an understanding of the fundamentals of building heat transfer. If the dynamic response of a building component is to be determined, graduate-level training in mathematics is required.

A minimum temperature difference between inside and outside air temperatures must be maintained for an HFT to respond with a measurable and usable output signal. Spurious voltage sources can induce fluctuations in the measurements; however, integration can be used to average out many of the fluctuations.

Mounting an HFT onto the exterior surface of a building component should be avoided since the sensitivity of the device will change with the changes in the outside air temperature.

To obtain a representative R-value at any location, the sensor should remain at that location for at least one diurnal cycle (24 hr), depending upon the thickness of the construction. Building enclosure systems consisting of masonry walls may require measurement over a period of many days.

New technology/developments

In studying the performance of building enclosures to improve their energy efficiency, it is sometimes necessary to measure heat flows that are relatively small and spatially nonuniform. Multiple HFTs can usually determine the area-averaged heat flow.

The Lawrence Berkeley Laboratory has developed an HFT, based on ac resistance thermometry, that accurately measures average heat flows over large areas. They have built several moderate-sized (0.09 m^2 or 1.0 ft^2) prototypes and are planning larger units (0.7 m^2 or 7.5 ft^2).

The same techniques can be used to construct larger HFTs, and average heat flows over large areas may be measured with comparable sensitivity by piecing together HFTs of a convenient size. Their work has exposed no fundamental difficulty, and the major difficulties are expected to be in protecting the wires in large units from strains and in developing a convenient method of calibration. A lower sensitivity could be attained by improving the design of the amplifier.

The most recent development in the use of HFTs is that of combining their use with a thermal imager to determine the proper placement of the sensor to avoid locations (framing members, insulation voids) not required for monitoring.

Cost

The cost of a heat flow sensor depends upon its size. The approximate cost of most small to medium size sensors is in the range of $100 to $300. Larger sensors will cost more. The total cost of a system (sensor and readout device) to monitor one location would be approximately $1,000.

PORTABLE CALORIMETER

Recently, the Building Research Division of the National Research Council of Canada (BRD/NRCC) developed a portable calorimeter (guarded hot box) for measuring on-site heat transmission through building components.

The calorimeter is a five-sided insulated box, the open side of which is sealed against the building component on the hot side. An electric heater located inside the box is thermostatically controlled so that the temperature is equal to the indoor temperature of the building enclosure. Since the reverse heat loss through the box and the loss where the box edge contacts the surface are essentially zero, the metered energy supplied to the electric heater is essentially equal to the heat transmission through the building component. This technique has the advantages that the measurement provides a minimum disturbance to the heat transmission and a sufficiently large measured

surface is considered to be more representative of the total performance of the building component than the smaller surface measured by an HFT. The accuracy of the technique is about 5%.

Before a calorimeter box measurement of a building component, a representative measuring site should be selected. While thermal anomalies need to be located, there is usually more interest in the performance of a building component in areas free of defects, unless the purpose is to measure the effect of thermal anomalies on the enclosure performance.

The calorimeter box is sealed to the measurement site. It is very important that a good seal be provided along the edge to prevent convective exchange between the calorimeter and the room air.

The measurement periods given in Table 4 should ensure accuracy to within 5% in determining the thermal resistance, R.

Table 4. Required measurement periods for various building components.

Component	*Measurement time (days)*
Built-up roof, concrete deck	6
Built-up roof, steel deck	0.5
Wood-frame cavity walls	1.0
Masonry walls	1–5
Metal curtain walls	> 0.5

Calorimeter box measurements should be carried out only during periods when the outdoor and indoor temperature difference is greater than 10°F (6°C). Solar radiation on walls in winter may frequently produce temperature differences less than 10°F. During the measurement, the indoor temperature should be thermostatically controlled at a constant level to minimize differences in the temperature between the calorimeter box and the room. Solar radiation and conditioned air from supply vents should not contact the calorimeter box.

The methods for interpreting HFT data are also applicable to data produced by this technique. However, the results are applicable to larger areas of the building components.

This technique has been used only by the National Research Council of Canada. They have constructed 10 portable calorimeters and private contractors have constructed portable calorimeters using the NRCC specification. The cost of construction is estimated to be from $800 to $1000. No data are available describing training requirements; however, they should be equivalent to those described for HFTs.

ENVELOPE THERMAL TESTING UNIT

The envelope thermal testing unit (ETTU) was developed by the Lawrence Berkeley Laboratory to evaluate the on-site transient thermal performance of walls. It consists of two "blankets" that are attached to opposite sides of a wall and through which the heat flux to the opposite wall surfaces can be controlled. This unit was designed to overcome some of the difficulties in using HFTs and calorimeters for the on-site evaluation of building components. Unlike those devices, the ETTU controls variation in heat flow and not temperature.

The term "blankets" is used because the units cover the test wall section and are slightly flexible so that they can be made to conform to slight irregularities on the wall surfaces. Placing the blankets in thermal contact with the wall eliminates complications associated with air film and considerably reduces the bulk of the unit.

Each blanket consists of a pair of large electric heaters separated by an insulating layer in which is embedded an array of temperature sensors. Each heater is designed to provide a heat output that is uniform over the whole area. A microprocessor-controlled data acquisition system determines a planned variation in heat flow and records the wall's response.

After calibration of the unit, the thermal resistance of a building component can be determined within ±5%.

This technique can be used where accurate determination of the thermal characteristics of the building enclosure are required. Its accuracy makes it suitable for verifying thermal specifications in new and retrofit buildings. Since it requires the application of both an exterior and interior blanket, it may be difficult to use on the upper stories of tall buildings and cannot be used in below-grade applications. This technique should be applicable to both cold and warm climates. Where possible it should be used after a thermographic survey.

The ETTU is limited in potential to being a research tool. It involves complex control circuits and, since it adds heat to the construction differently from the ambient conditions, it has serious problems with causing lateral heat flow and consequent spurious measurements.

Chapter 4. Building Enclosure System Evaluation—Air Leakage Measurement

DECAY (TRACER GAS)

Measurement and analysis

The leakage of air into and out of a building is one of the major components of heat loss. Although recent advances in instrumentation have made it possible to measure the air leakage rate of a building automatically, the techniques to obtain these data are both expensive and time-consuming. In attempting to assess the air leakage characteristics of a building, four questions must be answered:

- What are the measured air leakage rates under various climatic conditions and usage patterns?
- How tight is the building after retrofit measures are applied?
- Where are the leakage paths?
- What is the severity of each leakage path?

Air leakage is the uncontrolled passage of air into or out of a building. It can be measured under natural conditions by mixing indoor air with a tracer gas, that is, a gas not normally found in either outdoor or indoor air (such as sulfur hexafluoride) or by measuring the excess (indoors over outdoors) of a naturally produced component (CO_2, CO, or radon).

The infiltration rate of a building is usually determined by the tracer-gas dilution method. This method is very versatile and the simplest of the tracer-gas measurement systems. It can be used for short- and long-term measurements, and the measuring equipment may be located on site or the samples may be collected in air bags and analyzed off site.

The tracer-gas technique for measuring building air leakage consists of injecting a quantity of tracer gas such as sulfur hexafluoride (SF_6) in such a manner that it is well mixed and then measuring the rate cf decay of this gas.

After assuring that the initial quantity of gas is well mixed, concentration measurements are made at 5- to 15-minute intervals. The air leakage rate is then determined by a graph of the SF_6 concentration decay vs. time. The following instrumentation is used for these measurements:

1. A tracer gas monitor calibrated by the manufacturer or on site with mixtures of at least two different concentrations used in the range of the test.
2. A sampling network, consisting of tubing, tubing junctions, a pump, and an aspirator, that is used to draw samples from remote locations, blend them, and bring the blended sample to a convenient place for analysis.
3. Syringes.
4. Fans capable of circulating air throughout the building; the building's air-handling system can also be used.
5. Meteorology stations that record wind speed and direction and outside temperature.
6. An indoor temperature monitor.

Automated equipment developed by researchers at the National Bureau of Standards (NBS) and Princeton University has been used in the United States since 1974. These system use an electron-capture gas chromatograph that measures SF_6 in the parts-per-trillion (ppt) range. The unit pumps air through an aluminum oxide column that separates SF_6 from oxygen (O_2), which also captures electrons. The gases then pass through a detector containing a radioactive source of electrons. The decrease in the current established by the source is measured and converted into arbitrary concentration units. The column is flushed with argon (Ar) or nitrogen (N_2) between samples, depending on the type of detector.

Although exact SF_6 concentrations are not crucial to the method, it is important to calibrate the apparatus to ensure that operation is in the linear range. A linear response with a current corresponding to a potential of 70V or higher indicates proper detector operation. Earlier versions of these systems used mechanical sequencing timers to control sampling and injection and recorded the output on a chart recorder. The latest version consists of a microcomputer with two 5-1/4-in. dual-sided floppy disk drives, a real-time clock, a CRT terminal, an electron-capture-detector gas chromatograph, a 10-port sampling manifold, five injection units, and interfaces for both analog and digital data.

A less expensive method for obtaining these data consists of using concentration monitoring equipment placed in the building and analyzing air sample bags filled at intervals of 1 to 2 hours. Testing a dwelling includes the following steps:

1. Injection of SF_6—A quantity of SF_6 is injected into the dwelling so that the initial concen-

tration is 100 to 150 parts/billion (ppb) or approximately 10 to 15 mL per 1000 m^3 of living space. The gas is injected into each room in a quantity approximately proportional to the volume of the room.

2. Mixing of Tracer Gas—From 1/2 hour to 1 hour is allowed for proper mixing of the gas. If the dwelling is heated by a forced air system, the fan can be turned on to assist in the mixing; however, convection currents will mix the tracer gas on each floor of the dwelling if the doors between rooms are open.
3. Filling Air-Sample Bags—After adequate mixing of the tracer gas, one sample bag is filled (using a small pump) with air from each floor of the living space. The air-sample bags must be filled slowly to ensure the collection of representative samples.
4. Dissipation of Tracer Gas—One or 2 hours is allowed for the tracer gas to dissipate. The mechanical system is left in its normal operating mode during this time.
5. Filling Air-Sample Bags (Repeat)—The procedure in the third step is repeated with a second sample bag of air from each floor of the dwelling.
6. Shipping Sample Bags to Analysis Center—The sample bags are shipped to a center for analysis and measurement of the tracer gas concentration. The air infiltration rate is then computed.

According to some experts, a tracer gas should have the following attributes:

- Its content in the air must be relatively small, and there must be no source of it in the building.
- It must be possible to accurately detect a low concentration of the gas.
- Its density must be as near as possible to that of air.
- It must not react with the constituents of air or be adsorbed onto the surfaces of walls, furniture, clothes, etc.
- The gas must not be harmful to building occupants.
- It must not be flammable.
- The gas must be easy to handle, easily available, and inexpensive.

Another purpose of air leakage tests is to measure whether ventilation is adequate. There have been numerous complaints in office buildings in both the U.S. and Canada of symptoms related to insufficient clean air supply: headaches, nausea, fatigue, and respiratory symptoms. These complaints may be due to excessive concentrations of carbon monoxide, smoke, formaldehyde, or other contaminants, or to excessive relative humidity, heat, or insufficient air movement.

Failure to achieve specified building ventilation rates indicates a potential for employee complaints of symptoms and of contamination by such pollutants as radon daughters, which cause no complaints. Ventilation may be more adequate in some parts of a building than in others. Insufficient air movement may occur even when ventilation is adequate; however, an excessively low air exchange rate is *prima facie* evidence of poor air quality.

Accuracy

Errors in tracer gas concentration measurements are approximately 2.5%. This is negligible in comparison with the usual scatter caused by wind gusts, changing temperatures, and furnace cycling.

Advantages

Tracer gas methods are an important aid in determining the rate of air leakage or ventilation adequacy. The error rate is lower than with other air leakage measurement methods that rely on wind gusts, changing temperatures, and HVAC system cooling.

Tracer gas can be used for both short- and long-term measurement throughout the year. The injection and measurement may be done either manually or automatically, and a single detector can be used for a number of measurements.

With the air bag sampling method, operators need not be highly trained, and the measurement and analysis can be done either on or off site, which gives the method great flexibility.

Limitations

Only long-term average results representing different climatic conditions are useful for comparison with other buildings.

Since most leakage occurs on the windward and leeward faces of a building, poor construction may be missed by the tracer gas test. Tight control must be kept on the density of the tracer gas and the location of the detector, or spurious infiltration rates—high or low—could be registered. Moreover, the method will not provide the precise location of air leakage paths.

Uniform tracer gas distribution will be difficult to obtain in large buildings and those partitioned into many rooms, unless they have a central air handling system.

The cost may be very high and operation may require highly trained technicians unless the air bag sampling modification is incorporated.

New technology/developments

None.

Cost

The chromatograph-detector unit is compact, simple to operate, and costs approximately $6000 to $8000. It is portable, but tanks of SF_6 and Ar or N_2 must be transported along with it. An attachment is available so 10 sites may be automatically sampled almost simultaneously.

The complete automatic system costs approximately $20,000 and must be specially assembled. It has been used in air infiltration studies in large buildings.

CONSTANT CONCENTRATION (TRACER GAS)

Measurement and analysis

This method is similar to the decay method except that the time intervals between tracer injections are shorter. All constant concentration injection techniques now in use utilize automated systems.

British Gas Corporation method

The British Gas Corporation air infiltration unit is based upon a microprocessor and rapid sample analysis. Gas is released to maintain constant concentration in each room of a house. Rooms are monitored in sequence for 6 seconds each, an injection valve is opened, and the duration of injection is recorded.

The two most recent concentrations are used to vary the amount of N_2O injected prior to the next sampling with the concentration maintained at 50 ± 2 parts/million (ppm). Each of the injection lines is calibrated before the test so that the injection is suitable for each room.

This method has been used for almost 2 years with up to 12 rooms measured simultaneously. Six houses have been analyzed with an accuracy of ±10%.

National Research Council of Canada (NRCC) method

In this method, concentration is measured every 2 or 2-1/2 minutes. Fixed amounts of SF_6 can be injected up to 90 times over the next interval, with the intervals spaced as closely as 0.9 seconds apart. The tracer gas concentration is measured by the same electron-capture gas chromatography unit described for the tracer decay method. Since a level of 15 ppb SF_6 is generally maintained, the amount of tracer gas used during a test is very small.

The NRCC apparatus has been functioning for several years and is now available as a commercially packaged unit. This unit can hold SF_6 concentrations in a house constant to within 4% over 15-minute intervals and 2% over a 1-hour interval.

Kumar et al. (1979), in a report on two houses, claim that agreement between constant concentration and tracer decay methods was better than 2%. To achieve thorough mixing in these houses, the furnace fan was operated continuously.

Danish Institute of Technology method

The automated system of the Danish Institute of Technology is microcomputer-based. It has many similarities to the British Gas Corporation system. Injection of N_2O is essentially continuous. Small fans are located near the N_2O injection port in each room to promote rapid mixing. Ten solenoid valves control injection and another 10 control sampling to the infrared detector. The design also provides a tank of N_2O gas at 48 ppm to periodically check the design value of 50 ±2 ppm N_2O concentrations within the home. Temperature and humidity sensors are being added to further increase accuracy.

Metal tubes near door hinges are used to provide sampling paths so that door operation is unaffected. The N_2O injection orifices for each room are carefully designed and calibrated. The system can operate for up to 6 days unattended. Records are maintained on floppy disks, with a viewing screen provided to check on-site operation.

Swedish National Testing Institute method

The automatic measurement method of the Swedish National Testing Institute is similar to the Danish one. The short response time of the N_2O analyzer allows collection of a large number of samples. An arrangement of 10 tubes to the analyzer allows 9 air samples and one fresh air purge. The fresh air must be raised to room temperature to avoid analysis problems. The pumping system moves the samples to the analyzer through plastic tubes within the house. When operated from a van, special tubing is used to insulate the nine plastic tubes. Measurements are made at set intervals and used by the microprocessor to calculate air exchange rates for each room.

Advantages

Measurements may be taken over a long period, and there is a task-observable response to weather changes. In addition, since the gas injection rate is

directly proportional to the infiltration rate, data analysis is more direct. With this method, infiltration rates of building spaces that have separate air supply systems can be measured. Large air change rates can be generated with a measurement accuracy of 5 to 10%.

Limitations

Systems that use electron-capture gas chromatography have a major weakness in that with heavy usage the column and detector require considerable maintenance, cleaning, and calibration. The switching valve also requires maintenance. In addition, with these systems, zero drift of the detector is a continuing problem.

In all systems of this type, measurement is always a response to a previous tracer concentration, since the mixing of air and gas is not instantaneous.

The measurement system must always be automated, and no precise air path leakages can be identified.

CONSTANT FLOW (TRACER GAS)

Measurement and analysis

The constant flow method was developed at the Lawrence Berkeley Laboratory (LBL) to provide automated infiltration measurements in a test space at 30-minute intervals. The instrumentation originally used N_2O with an infrared analyzer, but because of exposure limits it was modified to use SF_6.

The system was designed to permit researchers to examine the effects of weather and mechanical systems on infiltration. The instrumentation contains a microcomputer that

- Controls the injection rate of tracer gas
- Selects the sampling port
- Processes and records weather and system data
- Calculates and records average infiltration values, and
- Computes a new injection rate based on the previously calculated infiltration rate to keep the concentration within a particular range.

The average infiltration monitor, developed at LBL, permits simple unattended measurement of the long-term infiltration rate of a building. The monitor minimizes both inconveniences to building components and the technical skills required to install the system. It consists of an injector and the sampler, each of which contains a small solenoid pump that is pulsed at a rate controlled by an internal timer. Each pump is either emptied by injecting tracer gas into the space or filled by sampling the mixture of tracer gas and room air in the space. The concentration is determined after the pump is emptied or filled.

Accuracy

Information on the accuracy of the constant flow method is not available.

Advantages

This method permits continuous measurements of the ventilation rate. No complex instrumentation feedback loops are required to maintain constant concentration, and inconvenience to building occupants is minimized.

Limitations

The infiltration rate may drop considerably during changing weather conditions, causing the concentration to rise beyond the limit of the detector.

The technique must be automated to achieve maximum efficiency.

The method does not provide a precise location of individual air leakage paths.

New technology/developments

None.

Cost

Cost information is not available.

FAN PRESSURIZATION

Measurement and analysis

Fan pressurization is used to measure the tightness of a building enclosure system independent of weather conditions. The building is pressurized or depressurized by a fan, and the air flow is measured. Buildings can be compared by generating the air leakage at a standardized pressure difference. A fan mounted in an airtight assembly is placed either in a window or doorway, and measurements are made in minutes. Inadequate mixing is not nearly as important a factor in fan measurements as it is in tracer gas measurements. To minimize natural pressure differences and to obtain measurable flow rates, large pressure differences are usually required. Use of a large fan or a number of smaller fans simultaneously may be required in medium-size buildings.

Tests are conducted as follows:

1. Observe the condition of the building, including windows, doors, walls, roof, and

floors. Measure and record the wind speed and outdoor and indoor temperatures.

2. Place the air-moving apparatus near the structure and connect the duct or blower door assembly to the building enclosure, using a window, door, or vent opening. Seal or tape openings to prevent leakage.
3. Calibrate the fan to obtain air flow rates if no other flow meters will be used.
4. Measure flow rates at pressure differences from 10 to 70 Pa at 10-Pa increments.
5. Calculate the airflow rates.

A uniform pressure is maintained in the building that is within 20% of the indoor-outdoor pressure difference. The maximum variation from stack or wind effect should be no more than 10% of the pressure difference. Tests are usually not made when wind speeds are above 9 mi/h (15 km/h).

The thermal stack effect is usually disregarded for one-story buildings. For two or more stories the stack effect usually results in a pressure difference of approximately 0.056 Pa/°F (or 0.1 Pa/°C) per story. At a temperature difference of 36°F (20°C), the stack effect in a 10-story building results in a pressure difference of approximately 20 Pa. An alternative technique uses the air handling system of the building to pressurize it; however, this method cannot be used to measure permeabilities of individual components such as windows or doors.

The following instrumentation is required:

1. Fan, blower, or blower door assembly, capable of establishing indoor-outdoor pressure differences in the range 10–70 Pa.
2. Manometer or pressure indicator capable of measuring pressure differences to within 2.5 Pa.
3. Air flow or velocity measuring system capable of measuring flow to within 6% of its average value. The instrument should be calibrated according to the manufacturer's instructions or in a calibrating wind tunnel.
4. Wind speed measuring device accurate to 1 km/h or 0.3 m/s (60 ft/min).
5. Temperature measuring device accurate to 2°F (1°C).
6. Air flow regulating system, e.g., a damper or variable motor speed control that will regulate and maintain air flow within specific limits.
7. Ductwork able to accommodate both pressurization and depressurization.

Accuracy

ASTM estimates the uncertainty of the measurements to be approximately 10%.

Advantages

The fan pressurization method is simple and can be used to compare air leakage rates of buildings at various times (e.g. before and after retrofit). The effectiveness of retrofit measures applied one at a time can be assessed.

No reference to wind and outside air temperature is required for data analysis.

This method can be used in conjunction with infrared thermography to locate leakage paths precisely.

Limitations

Under some circumstances the pressure differences generated are so great that the leakage paths may be quite different from those that occur under normal conditions.

It is difficult to isolate one pressurized space from an adjoining space, and it is difficult to pressurize adjoining spaces to maintain a uniform pressure difference.

New technology/developments

Pressure differences induced by fans are so large that wind has little effect by comparison. An alternative pressurization technique that uses pressures close to naturally occurring ones is the infrasonic or alternating pressure (ac) fan method. A piston inside the building or mounted in a wall alternately causes air to leak in and out. If the frequency is low enough, there is little compression and decompression. The frequency provides a means of distinguishing induced from natural pressurization; the latter can be electronically filtered. This method has not been widely used and it may prove as difficult to apply to large buildings as the fan pressurization test. For more on the ac method, see Sherman et al. (1981).

Infrasonic methods may be helpful in simulating natural conditions since they produce lower pressure differences than fans, but their relationship to natural conditions has not yet been determined.

Purchasing information

Cost

From $2500 to $10,000.

Manufacturers

Manufacturers include: Infiltec, Division of Saum Enterprises, Inc., P.O. Box 1533, Falls Church, Va. 22041, (703) 820-7696; Retrotec USA, Inc., 6215 Morenci Trail, Indianapolis, Ind. 46268, (317) 297-1927.

INFRASONIC SYSTEM

Measurement and analysis

In the frequency range 0.1–7 Hz, small buildings are characterized by one acoustic capacitance and one nonlinear leakage resistance. Infrasonic apparatus comprising a motor-driven source of known output, a pressure pickup, and a signal processor are used to measure air leakage.

The infrasonic system is composed of a portable source and a pressure sensor that are set up inside the building. The fixed displacement source alternately compresses and rarifies the air above a movable piston. The bottom of the piston supplies an alternating volume of air to the enclosed space. The piston has a peak-to-peak displacement of only 1.5 in. (3.81 cm), making its action more like a bellows.

The pressure sensor has a very thin plastic membrane across its opening. As the pressure and the space vary (due to the source), the membrane deflection is measured with an optical instrument.

The infrasonic system generates a very low frequency (approx. 1 Hz) of known magnitude. The source frequency is applied to the building interior, and the alternating component of inside pressure is a function of the type and size of leakage paths.

The pressure variations that must be detected are such that the sensor must be able to resolve 0.1 to 0.01 Pa. To prevent normal barometric pressure fluctuations from interfering with the measurements, the sensor chamber is provided with a very small slow leak.

The signal from the sensor is processed before it is passed to a chart recorder. The system also uses a sharp cut-off filter to attenuate ordinary acoustic noise above 7 Hz.

Accuracy

When compared with a blower door system, the air leakage data agree within 200%.

Advantages

Setup time is minimal since no pressure taps or through-the-wall vents are required.

Limitations

The accuracy of the infrasonic system is low. Poor agreement is due to wind gusts and instrument calibration.

Calculations of air leakage from an infrasonic test requires using the building volume and the measured frequency response curve.

New technology/developments

Sound is generated by a number of sources: tape player / speaker system, siren, horn, bells, etc. There are numerous sound detection systems, including a doctor's stethoscope and a small microphone attached to earphones with appropriate electronics. Both allow local sensing to pinpoint the leak. One approach that has proven effective is a tape recording of white noise and a rising-falling tone. The white noise sound is useful outside where other noise generation may prove objectionable.

Cost

Not yet available commercially.

SMOKE TRACERS

Measurement and analysis

Commercial smoke tracer units are available. These units provide smoke at a well-defined location so that in the presence of an air leakage site a stream of smoke extends to or from the opening.

Smoke tracer techniques employ both pressurization and depressurization of the building. Building depressurization / pressurization is effected by a fan, blower, blower door assembly, or the mechanical ventilating system of the building that can be used to move air through the conditioned space at flow rates so that leakage sites will flow air to meet the depressurization / pressurization requirement. The system is normally adjusted to provide steady air flow rates during the leak-site detection procedure.

Accuracy

Not applicable.

Advantages

Smoke tracers are easy to use. Visual sighting of smoke flow provides instant analysis of leakage sites.

Limitations

Smoke tracers give no quantitative information. In addition, the building may have to be evacuated before the procedure, and smoke moving through the enclosure system in a twisted path may be absorbed in the insulation or other materials.

New technology/developments

None.

Cost

From $100 to $10,000.

Chapter 5. HVAC System Evaluation

Temperature Measurements

LIQUID-IN-GLASS THERMOMETERS

Measurement and analysis

Any device that indicates temperature is a thermometer; however, in common usage the term signifies the ordinary liquid-in-glass indicating device. Mercury-filled thermometers have a useful range from –40°F or 0°C (the freezing point of mercury) to approximately 1000°F or 540°C (the softening point of glass). Thermometers are usually calibrated during manufacture at the freezing and boiling points of water, and the space between those points is evenly divided by scale divisions. Liquid-in-glass thermometers are calibrated for either full or partial immersion. If a thermometer is calibrated at full immersion and used at partial immersion, a correction factor must be applied to account for the temperature difference between the two.

Accuracy

The probable error for etched-stem liquid-in-glass thermometers is ±1 scale division.

Limitations

A thermometer used to measure gas temperatures can be significantly affected by radiation from the surrounding environment; therefore, it is necessary to minimize these radiation effects by shielding. All thermometers must come in contact with the medium that they are measuring; their limitations are similar to those that measure surface temperature. They can measure actual temperature without complex corrections for the characteristics of the medium; however, the measurement is only valid for that single location.

New technology/developments

None.

Cost

Liquid-in-glass thermometers can usually be purchased for a few dollars each in small lots or less in larger quantities.

THERMOCOUPLES

Measurement and analysis

When two wires made of dissimilar metals are joined, a thermocouple junction is formed. A voltage, which depends upon the materials of the wires and the temperature of the junction, exists between the wires. When the wires are joined at two points, a circuit is formed. If one junction is kept at a temperature different from the other, an electric current flows through the circuit. This phenomenon is used for temperature measurements in thermocouple systems: the reference junction is kept at a constant known temperature, while the other is at the point where the temperature measurement is required. Advances in solid-state circuitry have made digital readout devices possible, made both as a straight millivolt or microvolt meter and as a packaged thermocouple readout. The latter instrument only requires attachment of a thermocouple of proper composition to provide direct meter reading of temperature. Accuracies approaching or even surpassing those of the commonly used potentiometers can be attained, depending on the quality of the instrument.

The choice of materials for the thermocouple wire is determined by the temperature to be measured, the protection from corrosion, and the precision and service required. In general, copper vs constantan is suitable for temperatures up to 700°F (370°C), iron vs constantan up to 1500°F (815°C), and chromel vs alumel up to 2200°F (1205°C).

If they are to be used in heated air or gases, thermocouples are often shielded, as are thermometers, and aspirated thermocouples are sometime used.

Thermocouples can indicate or record temperatures at remote points and temperatures may be obtained from within thin materials, narrow spaces, or otherwise inaccessible locations.

A series arrangement of thermocouples, often called a thermopile, can have extreme sensitivity and is useful in detecting very small changes and differences in temperature. The thermocouple is

particularly useful in determining a surface temperature and may be attached to a metal surface in one of several ways. For temporary arrangements, couples may be attached by means of tape, adhesive, or a putty-like material. To minimize the possibility of error due to heat conduction along the wires, a surface thermocouple should be made of fine wires that are held in contact with the surface for an inch or so from the junction. The wires must be insulated except at the junction.

Accuracy

The degree of accuracy depends on the choice of materials used for the thermocouple wire, which in turn is dependent upon the temperature to be measured. Generally for temperatures up to 2200°F (1205°C) the accuracy can vary from 0.1 to 15°F (0.05 to 8°C). For temperatures from 500 to 3000°F (260-1650°C) the accuracy can vary from 0.1 to 5°F (0.05 to 2.8°C).

The thermocouple material used for standardizing other thermocouple measurements is accurate but expensive and requires expensive measuring devices. Other materials are less accurate and are subject to oxidation.

Advantages/limitations

Since thermocouples are used in the probes of surface temperature measuring thermometers, the advantages and limitations discussed in that section are also applicable here.

New technology/developments

Thermocouple assemblies feature quick-disconnect plugs, miniature all-purpose heads, very-high-temperature probes, extremely flexible probes for bending around inaccessible corners, and very thin-diameter, low thermal inertia, fast-response thermocouples that are used for measurements in gas flow systems.

Cost

A typical cost for a thermocouple assembly is $100 or less. This does not include the cost of the measuring device.

RESISTANCE THERMOMETERS

Measurement and analysis

Resistance thermometers depend for their operation upon the increase in resistance of a sensing element (usually metal) with an increase in temperature. Their temperature range parallels that of thermocouples, although readings tend to be unstable above 950°F (510°C). For accurate results the entire thermometer coil must be exposed to the temperature to be measured.

Thermistors (semiconductor compounds) are a special class of resistance thermometers that exhibit large changes in resistance with temperature, usually decreasing with temperature increase. Small formed shapes of compound, selected for a particular application and temperature range, are made and heat-cured. The thermistor element is connected by lead wires to a digital ohmmeter or special Wheatstone bridge for readout. Thermistors can be purchased with a known temperature vs resistance curve or as uncalibrated units.

Accuracy

In the range of -320 to 1800°F (-196 to 982°C) the accuracy of a resistance thermometer ranges between 0.02 to 5°F (0.01 to 2.8°C). When measuring gas temperatures its accuracy is affected by radiation from surrounding surfaces.

Advantages

Compared to the thermocouple, the resistance thermometer does not require a cold junction, and it can be scaled for more accurate measurements. It gives best results when used to measure steady or slowly changing temperatures. Of all usable metals, platinum best meets the requirements of thermometry because it can be highly refined, resists contamination, and is mechanically and electrically stable. The relationship between temperature and resistance is nearly linear, and drift and error with age and use are negligible. Production units can be closely matched in calibration.

New technology/developments

A major advance has been the development of thin-film sensing elements for platinum resistance thermometers that combines the precision measuring capability of platinum with the rapid response time of a thermocouple.

Cost

Depending upon the material used in the sensing element the cost of a resistance thermometer can be up to and slightly over $100. Thermistors are available at $10 and up.

GLOBE THERMOMETER

Measurement and analysis

The radiant temperature in conditioned spaces must be measured to determine comfort levels, as well as operation of electronic instrumentation.

A globe thermometer is commonly used to measure mean radiant temperature (MRT). This instrument consists of a 6-in.-diameter hollow copper sphere coated with flat black paint; it has a temperature probe at its center. The temperature in the globe at equilibrium is the result of a balance between the heat gained or lost by radiation and the loss or gain by convection.

A two-sphere radiometer may also be used to measure MRT. This instrument uses two spheres approximately 2 in. in diameter; one is gold-plated and the other is black. The two spheres are heated electrically to the same temperature, eliminating differences in convection. The difference in energy to maintain temperature equilibrium is measured, and the MRT of the space can be calculated.

Accuracy

The accuracy would be determined in general by the type of temperature probe used in the sphere.

Limitations

The time constant is long, approximately 10–15 minutes. Correction for air temperature and local air speed must be made to determine temperatures accurately.

New technology/developments

The plane radiant thermometer is an electronic device that determines the radiant temperature in one (or two opposite) direction(s).

Several commercial devices have recently become available.

Cost

No cost data are available.

LIQUID CRYSTAL DISPLAY (LCD) THERMOMETERS

Measurement and analysis

As the temperature changes, these heat-sensitive indicators turn color through a chemical reaction. They can be used to measure both air and surface temperatures.

Accuracy

Accuracy of a typical single-temperature rating is within 1% of that rating.

Advantages

LCDs are low cost and they adhere to most surfaces.

Limitations

LCDs are capable of measuring localized temperatures only; remote temperatures cannot be measured.

The user must be close to the LCD to observe the temperature change.

New technology/developments

None.

Cost

Depending upon quantity, the cost varies from less than a dollar to less than $10.

Humidity Measurements

PSYCHROMETER

Measurement and analysis

Any instrument capable of measuring the humidity or psychrometric state of the air is a hygrometer. A psychrometer is a particular kind of hygrometer that consists of two temperature sensors, one of which has a cloth wick applied to it. The wick is wetted with distilled water and ventilated with air moving at a sufficient rate, relative to the instrument. Experiments have shown that the evaporative cooling produces a wet-bulb temperature approximately equal to the thermodynamic wet-bulb temperature. The difference between the dry-bulb temperature and the wet-bulb temperature is called the wet-bulb depression. In the sling psychrometer, two thermometers are mounted side by side in a frame fitted with a handle by which the device can be whirled through the air. The motion is continued until the thermometer readings become steady. In the ventilated aspirated psychrometer, the thermometers remain stationary and a small fan or blower or a syringe is used to move the air across the thermometer bulbs.

Other temperature sensors, such as thermocouples and thermistors, are also used and can be adapted to record temperatures or for use where a small instrument is required.

Charts and tables are available that show the relation between the temperatures and humidity. Data are usually based on a barometric pressure equal to one standard atmosphere. A correction must be included for variations in barometric pressure.

For air temperatures below 0°C (32°F), the water on the wick may either freeze or supercool; its state must be known and the correct table or chart used, since the wet-bulb temperature for ice is different than it is for water.

Accuracy

In the range from 0 to 500°F (–17.8 to 260°C) the accuracy is 0.3 to 3% of the relative humidity.

Advantages

Psychrometers are used as a standard for humidity measurement.

Limitations

Psychrometers are sensitive to air moving across the thermometer bulbs. The accuracy decreases as humidity increases. They are temperature-dependent and difficult to use at subfreezing temperatures. They require a moderate amount of maintenance. The wick must be kept clean and the wet bulb should have distilled water.

New technology/developments

None.

Cost

Psychrometers cost up to $100, depending on the degree of accuracy.

DEWPOINT HYGROMETER

Measurement and analysis

In the most common form of these instruments, means are provided for cooling and observing the temperature of a surface exposed to the air. The highest temperature at which condensation occurs on the surface is taken as the dewpoint temperature of the air. This temperature may be used with charts and tables to determine the relative humidity of the air. A bright surface or metallic mirror is usually used with various methods to cool it, including evaporation of a refrigerant or a stream of air passed through dry ice. In some systems, the presence of condensation is detected visually. Thermoelectric cooling is used in automated systems with photoelectric cells to detect the presence of a moisture deposit and to accurately control the mirror at the dewpoint temperature. In automated systems, the dewpoint temperature is displayed on a dial, and provision is usually made for recording.

An instrument in which the temperature varies with the ambient dewpoint temperature is designated as a heated electrical hygrometer. This device usually consists of a substrate covered by glass-fiber fabric, with a spiral winding for electrodes. The surface is covered with a salt solution, usually lithium chloride. When in operation, the flow of electrical current through the salt film heats the sensor. The resistance characteristics of the salt are such that a balance is reached with the salt and its critical moisture content corresponding to a saturated solution. The temperature of the sensor then adjusts automatically so that the water vapor pressure of the salt film is equal to that of the ambient air.

Accuracy

Type	Range (depression °F/°C)	Accuracy (depression °F/°C)
Condensation	(−180)–200/(−118)–93	0.2–2/0.1–1
Salt-phase transition	0–160/(−18)–71	1–2/0.5–1

Limitations

The condensation or chilled mirror hygrometer is delicate, expensive, and must remain clean in order to provide accurate readings. Some difficulty can be expected with the supercooling effect. When lithium chloride is used in the salt-phase-transition-type hygrometer, it cannot be used to measure relative humidity below approximately 15%, and it has an upper dewpoint temperature limit of about 160°F (71°C).

New technology/developments

None.

Cost

No cost data are available.

DIMENSIONAL-CHANGE HYGROMETER

Measurement and analysis

Many organic materials change in dimension with changes in humidity; this action has been used in a number of simple and effective humidity indicators, recorders, and controllers. Motion caused by changes in dimension through a linkage causes a pointer to move across an indicating dial, moves a pen across a recording chart, or actuates a pneumatic or electric control mechanism.

Organic materials commonly employed are human hair and animal membrane, animal horn, and wood. Other organic-based material like paper, nylon, and Dacron are also used.

Accuracy

In the temperature range between −40 to 150°F (−40 to 66°C) and the full humidity range from 0–100% relative, a typical accuracy for a dimensional-change hygrometer is 3% relative humidity.

Advantages

Dimensional-change hygrometers can read directly in relative humidity, and they are simple and inexpensive in comparison with most other types.

Limitations

No organic material has been found that can be relied upon to consistently reproduce its action over an extended period of time, and the responses may be significantly affected by exposure to extremes of humidity. These devices require initial calibration and frequent recalibration or setting, especially when going from one humidity extreme to another.

New technology/developments

None.

Cost

No cost data are available.

ELECTRICAL IMPEDANCE HYGROMETER

Measurement and analysis

Any substance absorbs or gives up moisture with changing relative humidity and exhibits corresponding changes in its electrical impedance. The sensor in this type of hygrometer consists of dual electrodes on a substrate. It is coated with a film, usually containing a salt, in a binder to form an electrical connection between the windings. Means are provided to determine the resistance of the film. The relation of sensor resistance to humidity is represented by graphs. Since the sensor displays a sensitivity to temperature, these graphs consist of a series of curves, each one being suitable for a given temperature.

Accuracy

In the range from −40 to 150°F (−40 to 66°C), the accuracy varies from 1.5 to 3% rh.

Advantages

An electrical impedance hygrometer is susceptible to excessive humidities and to a variety of vapors. It should be calibrated periodically.

Limitations

This type of hygrometer displays a high sensitivity to humidity change.

New Technology/Developments

None.

Cost

No cost data are available.

ELECTROLYTIC HYGROMETER

Measurement and analysis

Air is commonly passed through a tube, where the moisture is absorbed by a desiccant and electrolyzed. The air flow is regulated, commonly at 100 cc/min STP. The electrical current required for electrolysis can be related to the humidity level. The instrument is commonly designed for use with moisture-air ratios in the range of 1 to 1000 ppm, but can be obtained for use with higher humidities.

Accuracy

In the range from –100 to –5°F (–73 to –20.5°C) depression, the accuracy is 3% of the scale range.

Limitations

The use of electrolytic hygrometers is ordinarily limited to low humidities.

New technology/developments

None.

Cost

No cost data are available.

GRAVIMETRIC HYGROMETER

Measurement and analysis

The humidity level can be measured by extracting and weighing the water vapor in a known quantity of air. For precise laboratory work, powerful desiccants, such as phosphorus pentoxide and magnesium perchlorate, are used for the extraction process, while for some purposes calcium chloride or silica gel may be satisfactory. Freezing the water vapor out of a measured stream of air with solid carbon dioxide and weighing the ice is a similar operation.

A commercial system for continuous measurement of humidity uses piezoelectric crystals coated with an absorbent material that reaches a moisture content that is dependent on the ambient humidity. The natural frequency of the crystal varies with the mass of coating and the moisture.

Accuracy

0.1 to 2%.

Limitations

Special equipment and extreme care are required for high accuracy.

New technology/developments

None.

Cost

No cost data are available.

Velocity Measurements

ANEMOMETERS

Measurement and analysis

Heating and air-conditioning engineers are called upon to measure the flow of air more often than that of other gases. Usually the air is measured at or near atmospheric pressure. Under this condition, air can be treated substantially as an incompressible fluid.

A detecting vane anemometer consists of a pivoted vane enclosed in a case. Air exerts a pressure on the vane as it passes through the instrument, and the movement of the vane is resisted by a spring and a magnet. The instrument gives instantaneous readings of directional velocities. With fluctuating velocities, it is necessary to average swings of the needle.

The propeller or revolving-vane anemometer consists of a wind-driven wheel connected through a gear train to a set of recording dials that read the linear feet of air passing in a measured length of time. Each instrument requires individual calibration. At low velocities the friction drag of the mechanism is considerable. To compensate for this, a gear train that overspeeds is commonly used.

A cup anemometer is almost universally used for measuring wind speeds. It consists of three or four hemispherical cups mounted radially from a vertical shaft. Wind from any point of the compass will cause the cups and shaft to rotate. The instrument is so constructed that wind speeds may be recorded or indicated electrically at some remote point.

Measurement of low air velocities (0–100 ft/min, or 0–31 m/min) is particularly difficult for the instruments described above. The flow pattern is very unstable, causing the turbulence level to be of the same order of magnitude as the velocity. Useful data can be obtained with any of several instruments, if they are maintained in calibration and the user understands their operation and limitations. Several types of thermal anemometers (directional and nondirectional) are applicable to this range, but their accuracy is questionable at the lower end.

If a suitable sensing element is heated electrically at a fixed rate and exposed to an air stream, its temperature is determined by how fast the air stream is conducting heat away from it. Therefore, its temperature is a measure of air velocity. In the hot-wire anemometer, a very thin heated wire is used as a resistance-thermometer element whose temperature may be determined accurately.

The hot-wire anemometer is a general-purpose instrument for air flow measurements. Typical applications are:

- Troubleshooting and the balancing of heating, ventilating, and air-conditioning systems by measuring duct air velocities
- Monitoring outdoor air movements
- Flow measurements for performance tests on ventilation fans
- Velocity profiles in large ducts
- Calibration of other air flow meters.

The anemometer can be conveniently used to measure the total mass flow of air in a pipe or duct. It is usually necessary to take measurements at various points in the duct to determine a velocity profile. Then the best placement of the sensor can be made to achieve the desired relationship of mass flow rate and velocity.

A hot-wire anemometer system consists of a hot-wire sensor, an electronic module containing a power supply, amplifiers, and feedback circuits, and a suitable data recorder. A voltmeter and an electronic filter are often used in turbulence studies.

Sensors for anemometer systems are available in a wide assortment of types and sizes. A typical hot-wire sensor is 1 to 2 mm long, 5 microns in diameter, and made of platinum-coated tungsten. The sensor completes one arm of a Wheatstone bridge circuit and is heated to a temperature significantly higher than the fluid temperature. The electrical power supplied by the anemometer to the hot-wire, and dissipated into the fluid, is related to the instantaneous velocity of the fluid over the wire.

Two basic types of anemometer systems are used: constant current and constant temperature. In the constant current anemometer, the electrical current supplied to the sensor is kept constant and any temperature change is a measure of air flow. In the constant temperature anemometer, the temperature of the hot-wire sensor is kept constant and the electrical energy needed to hold this temperature constant is a measure of air flow. For either system, the voltage drop across the wire is proportional to the instantaneous fluid velocity over the wire. The relationship between sensor voltage drop and fluid velocity must be carefully determined by calibration. The calibration process should be con-

ducted in a suitable device (e.g. miniature wind tunnel, water tunnel), using the fluid of interest at the temperature of interest.

The useful frequency response of an anemometer system can be as high as 45 kHz. A hot-wire anemometer is capable of measuring very rapid velocity fluctuations.

The heated-thermocouple anemometer is calibrated to give velocity in terms of the differential voltage between heated and unheated thermojunctions exposed to an air stream.

In the heated-bulb anemometer, a heating wire is wound around a mercury-in-glass thermometer, and the temperature difference between this thermometer and a similar unheated one serves as an index of air speed.

Accuracy

Anemometer	Range (ft/min)	Range (m/min)	Accuracy (%)
Deflecting vane	30–24,000	9.2–7385	5
Revolving vane	100–3000	30.8–923	5–20
Heated thermocouple	10–2000	3.1–615	3–20
Hot-wire	1–1000	0.3–308	1–20
Heated bulb	<60,000	<18,460	1–10

Limitations

Anemometer	Limitations
Deflecting vane	Large 1/2–3/4 in. diameter probe. Tubes connecting sensor head to body are somewhat awkward.
Revolving vane	Subject to error with variations in velocities with space or time; easily damaged.
Heated thermocouple	Accuracy of some types not good at lower end of range. Steady-state measurements only.

A hot-wire anemometer is a sophisticated, complex, delicate, and costly instrument. The principal advantages of hot-wire anemometer systems are:

- High-frequency response suitable for transient velocity and turbulence measurements
- The ability to measure accurately very low velocities in gases and liquids
- The availability of specialized sensors and accessories
- The small-diameter probe with flexible connection to instrument body.

All anemometers need periodic calibration.

New technology/developments

Devices have been developed that are compact enough to fit in a shirt pocket, have retractable self-stowing probes, are ultra-low-powered (AAA cells), and extremely rugged.

Purchasing information

Cost

$150 to $2200.

Manufacturers

Manufacturers include: Alnor Instrument Co., 7555 North Linder Ave., Skokie, Ill. 60077, (312) 647-7866; Kurz Instrument, Inc., P.O. Drawer 849, Carmel Valley, Calif. 93924, (800) 424-7356 or (408) 659-3421.

PITOT TUBE

Measurement and analysis

The Pitot tube, used in conjunction with a manometer, provides a simple method of determining the air velocity at a point in a flow field.

The type of manometer to be used with a Pitot tube depends upon the magnitude of the velocity pressure being measured and the accuracy desired. At velocities greater than 1500 ft/min (460 m/min), a draft gauge is usually satisfactory. If the Pitot tube is being used to measure low air velocities, a precision manometer is essential.

Many forms of Pitot tubes have been used and calibrated. To meet special conditions, different sized Pitot tubes that are geometrically similar to the standard tube can be used.

Accuracy

Instrument	Range (ft/min)	Range (m/min)	Accuracy
Micromanometer	180–10,000	55–3077	1–5%
Draft gauges	600–10,000	185–3077	
Manometer	10,000 up	3077 up	

Limitations

To obtain a velocity profile across a duct, a traverse of many readings must be taken. Pulsating or disturbed flow in a duct will result in erroneous readings; therefore a Pitot tube must be located sufficiently far from the source of disturbance to avoid those errors. This method is inapplicable in

many cases because of its lack of precision at low velocities or the impracticability of taking traverses where many test runs are in prospect.

New technology/developments

None.

Cost

No cost data are available.

AIRBORNE TRACERS

See also *Chapter 4, Air Leakage Measurement.*

Measurement and analysis

Tracer techniques are suited to making velocity measurements in an open space. Typical tracers include smoke, feathers, pieces of lint, and radioactive and nonradioactive gases. Measurements are made by timing the rate of movement of the tracers or by monitoring the change in their concentration level.

Smoke is very useful in studying air movements and can be obtained from titanium tetrachloride or by mixing potassium chlorate and powdered sugar and firing the mixture with a match. Titanium tetrachloride smoke can be easily handled in a small pistol-like ejector. Smoke tubes, candles, and bombs are available for studying airflow patterns. Gas tracers are a useful method for studying complex ventilation problems.

Accuracy

The accuracy of airborne tracers is from 10 to 20% over a range of 5 to 50 ft/min (1.5 to 15 m/min).

Advantages/limitations

See *Chapter 4, Air Leakage Measurement.*

New technology/developments

An infrared radiation-absorbing tracer gas technique using nitrous oxide (N_2O) and a thermal imaging system has been developed by the Architectural and Building Sciences Division of Public Works Canada (PWC) to illustrate patterns of air flow from air-conditioning supply diffusers. Air flow patterns are recorded in real time on video tape with an infrared camera and N_2O.

A typical diffuser test setup contains a screen that is heated and located some distance behind the diffuser. The space partitioning arrangement is not changed from that found in actual practice, and the thermographic scanner is located at as high an elevation as is practicable. N_2O is then introduced into the diffuser air stream where it appears to the scanner as a smoke-like image. The images can be enhanced by the use of a computer; the background may or may not be removed during this process to provide a clear image of the exact path of the tracer.

The PWC data indicate that some types of air diffusers provide good penetration of supply air into the work area under almost any conditions. These diffusers, however, are generally considered to be less desirable because they create strong downdrafts of cooled air and cause discomfort. The "draftless" diffusers, on the other hand, are affected by furniture layouts and diffuser flow rates. When air flow rates are high there is good penetration of supply air in variable air volume systems. When air flow rates are decreased according to lower cooling requirements, up to 90% of supply air does not reach the occupant.

Cost

From \$20 to \$5000.

Volume Measurements

VENTURI, NOZZLE, AND ORIFICE FLOW METERS

Measurement and analysis

Air volume in HVAC systems may be determined by several methods. Some methods require in-place sensors, others may be performed in installed systems. Unlike balance measurements, which are often made at terminal units, some volume measurements may be required in system ducts for optimal load management or for performance analysis.

Gas and liquid mass or volume flow rates are most often determined by measuring the pressure difference across an orifice, nozzle, or Venturi tube. The orifice is more easily changed than the nozzle or Venturi tube and is less affected by a change of the Reynolds number. The nozzle is often preferred to the orifice because of its relative freedom from the influence of approach conditions and the accurate predictability of its coefficient. The Venturi tube is in essence a nozzle followed by an expanding recovery section to reduce the net pressure drop.

The flow meters are usually used to measure fluid flow through pipes, ducts, and plenums.

Accuracy

The accuracy is 1% above a Reynolds number of 5000.

Limitations

The accuracy is affected by approach conditions.

New technology/developments

None.

Purchasing information

Cost

From \$1500 to \$3000.

Manufacturers

See *Chapter 6, Energy Metering.*

DISPLACEMENT METERS

Measurement and analysis

Many types of displacement meters are available to measure liquid or gas flow. Two types are gas meters, which employ leather bellows, and wet test meters, which use a water displacement principle. The Thomas meter has been used in the laboratory to measure high gas flow rates with a small pressure drop. The gas is heated and the temperature rise is measured by two resistance thermometer grids. Knowing the heat input and temperature rise, the flow is calculated as the quantity of gas that will remove the equivalent heat at the same temperature rise.

Accuracy

Instrument	Accuracy
Displacement meter	0.1–2% up to 1000 ft^3/min (depending on type).
Gasometer	0.5–1.0%
Thomas meter	1% over any range.

Limitations

Some displacement meters require calibration and are used in applications where relatively small volume flows at high pressure drops occur. Gasometers are used in short duration tests and for calibrating other flow methods. The Thomas meter is used primarily to measure the flow of gases and can usually only be justified where high accuracy requires an elaborate setup.

New technology/developments

None.

Purchasing information

Cost

\$100 to \$2000.

Manufacturers

See *Chapter 6, Energy Metering.*

ROTAMETER

Measurement and analysis

The rotameter is used for permanent installations where high precision, ruggedness, and ease of operation are important. Its most frequent use is in the measurement of liquids or gases in small-diameter pipes. For ducts or pipes over 6 in. in

diameter, the expense of this meter may not be warranted. In large systems, however, the meter might be placed in a bypass line and used in conjunction with an orifice.

In its most common form, the rotameter consists of a float that is free to move vertically in a transparent tapered tube. The fluid enters at the narrow bottom end of the tube and moves upward, passing through the annulus formed between the float and the inside wall of the tube. At any particular rate of flow, the float assumes a definite position in the tube, its location indicated by means of a calibrated scale on the tube.

This type of flow meter is usually furnished in standard sizes calibrated by the manufacturer for specific fluids. Its compactness, reliability, and ease of installation are particularly advantageous when many measurements of the same type are to be made.

Accuracy

Accuracy is 1% over any range of measurements.

Advantages

The rotameter is compact, reliable, and relatively easy to install.

Limitations

The instrument must be calibrated for each specific fluid by the manufacturer.

New technology/developments

None.

Purchasing information

Cost

From $300 to $3000.

Manufacturers

See *Chapter 6, Energy Metering*.

TURBINE FLOW METERS

Measurement and analysis

Turbine flow meters are volumetric sensing meters that have a magnetic turbine rotor suspended in the flow stream in a nonmagnetic meter body. The fluid stream exerts a force on the blades of the rotor, setting it in motion and converting the linear velocity of the fluid to an equivalent angular velocity. The rotational speed of the turbine is proportional to the fluid velocity and to the volume rate of flow of the fluid.

The speed of the rotor is monitored by an externally mounted pickoff assembly. Two types of pickoffs are used: magnetic and radio frequency.

Since the output frequency of the turbine flow meter is proportional to flow rate, every pulse from the meter is equivalent to a known volume of fluid that has passed through it; adding these pulses yields total volumetric flow.

Accuracy

Accuracy is 0.5% over any range of flow.

Advantages

Some meters may be used in bidirectional flow applications.

New technology/developments

None.

Purchasing information

Cost

From $2000 to $3500.

Manufacturers

See *Chapter 6, Energy Metering*.

POSITIVE DISPLACEMENT METERS

Measurement and analysis

Many types of positive displacement meters are available for measuring total liquid or gas flow rates. In this type of meter, the fluid flows into compartments of definite size. As the compartments are filled, they are rotated so that the fluid discharges from the meter. The rate of flow through the meter is equal to the product of the size of the compartments, the number of compartments, and the rate of rotation of the rotor. Most of these meters have a mechanical register that is calibrated to show total flow.

Novel and more sophisticated positive displacement flow meters have become commercially available. These meters use a metering gear pump (or a special blower), a transducer that senses the pressure difference across the pump, and a feedback system that controls the speed of the pump and maintains a zero pressure drop across the pump.

Accuracy

Using positive displacement meters with electromechanical feedback, fluid flow rates from 0.10 to 150 gal/min (0.40 to 568 L/min) have been measured with accuracies of better than 0.10%. Because

of the zero pressure drop across the meter, accurate measurements near the boiling point of liquids can be made.

New technology/developments

None.

Purchasing information

Cost

From $500 to $2500.

Manufacturers

See *Chapter 6, Energy Metering*.

Chapter 6. Energy Metering

ENERGY MANAGEMENT OBJECTIVES

Energy management includes energy metering. The type of energy metering system that is required depends on the functions the metering must serve to meet the energy management system needs. For instance, if the only need for energy metering is for billing on a facility-wide basis, then only a centrally located metering system is needed at the heating plant or substation. On the other hand, if energy usage is to be paid for by many different users within a facility, then each energy accountability unit needs a metering system so that the information needed for user-motivated conservation and billing is generated.

Energy conservation is often most effectively pursued if a small user group—an individual, a family or a small office—is metered and billed for the energy it uses and there is direct feedback to the individuals who control the energy use. At the other end of the spectrum, if metering is facility-wide and large numbers of users are contributing to a very large total energy consumption, individuals or small unit users have little feedback on the effectiveness of their conservation measures, and often the tendency is for individuals to become insensitive to energy use and the need for conservation.

Energy metering is expensive. So is energy use. A balance must be reached so that the metering that is installed produces savings in energy use equal to or greater than the cost of installing and operating meters. Utility companies install meters on each user unit, whether it be a family, an office, or a factory, because the information is needed for billing purposes, and the cost of metering is built into the cost of service to the customer. But for a large facility that either generates its own energy or distributes purchased energy to many user groups within it, the situation appears differently. Bills are not usually sent out to each user group. Instead, the cost of energy is totalled and all users share equally. In this system, individual user group energy use is not known, so inappropriate or wasteful energy use is difficult to pinpoint and correct.

Energy use meters provide information that may be used in several ways to help reduce energy usage, as described below.

Providing information for usage centers

Where energy use responsibility is tied to payment and comes out of each usage unit's annual budget, where there is consumer accountability, the energy meter provides the information necessary to allow local usage units to monitor, control, and assess their own energy conservation measures.

Monitoring energy use to determine equipment malfunction

Some equipment malfunctions are not obvious and are often detected through observing energy usage over a period of time. Inefficiencies due to equipment malfunction often go undetected for months unless increased energy usage is measured, observed, and investigated. Ideally it should never be necessary to find out about malfunctions this way because preventive maintenance should keep equipment operating so that this does not occur. However, many facilities are not able to sustain an effective preventive maintenance program, and malfunctions do occur.

Monitoring energy to measure conservation effectiveness

The effect of conservation measures on energy use can be observed with the information gained from energy metering. This allows the energy manager to compare predicted energy savings with actual energy saved. By substantiating the cost-effectiveness of energy conservation measures, the energy manager builds a data base for the facility that makes future predictions more accurate and new programs easier to sell.

Monitoring energy to measure the impact of new users

When new systems are installed, new departments added, new managers put in place, or new operating procedures adopted, the energy monitoring system can help the energy manager evaluate the impact of these changes. Energy use requirements can then be planned more effectively.

Long- versus short-term energy monitoring

Where energy is being billed to user groups, long-term energy monitoring is required. In this

way energy use is totaled in the form of kilowatt-hours, pounds of steam, Btus, or gallons of oil and is used to allocate the cost of energy to the users. However, if the user is very large and subunits are not to be held directly accountable for their usage or billed for it, then subunit system efficiency can often be monitored with short-term energy meters that are installed temporarily in the energy line to monitor energy use for a day, a week, a month, or whatever length of time is required to accommodate the energy manager's needs.

From these considerations, it can be seen that the energy manager must decide what overall energy management strategy is to be employed before deciding on energy metering equipment.

OPERATION AND USE OF ENERGY METERS

Energy supplied in the form of gas or liquid, such as steam, air, water, or oil, is usually measured by a device that measures the volume of material as it flows through pipes from its source to its point of use. The volume measurement may be direct, as in the case of a steam condensate meter, which takes all the condensate passing through it and measures its volume, or calculated, based on the measurement of pressure or velocity in a pipe of known dimensions and flow characteristics, as in the case of a turbine meter in a hot water or steam line.

The volume flow measured or computed is then converted to mass flow, usually in terms of pounds or kilograms. This conversion is simple for liquids and for gases at constant known conditions of temperature and pressure. For gases with varying conditions, however, temperature and pressure need to be monitored to convert accurately the meters' volumetric readings to mass flow and finally to energy flow.

The usable energy stored in a nonfuel gas or liquid depends on its beginning and ending temperature and its phase change characteristics. For instance, if the temperature of 1 lb of water drops 1°F, it gives off 1 Btu (British thermal unit) of energy. On the other hand, if 1 lb of steam changes phase and condenses to water with no temperature change, it gives off approximately 1000 Btu. Thus, to find the energy flow of a gas or liquid, one needs to determine the beginning and ending temperatures and, if a phase change (gas to liquid or liquid to solid) is involved in the process, the phase change characteristics of the material.

Electrical metering is available to measure both kilowatt-hours and kilowatt demand. The kilowatt-hour is a unit of electrical energy. The kilowatt is a unit of electrical power, but the rate of use of electrical energy is measured in kilowatt-hours per unit time. In alternating (ac) currents the measure of electrical power and energy is complicated by a factor known as power factor. Normally one thinks of electrical power, the kilowatt, as EI, a product of the voltage E and the current I. Because of what is called reactance in an ac circuit, caused by motors, transformers, and other electrical equipment, the current gets out of phase with the voltage. If one takes the product of EI in an ac circuit, one will obtain the apparent power of the system. The apparent power is always equal to or greater than the real power of the system. The real power is the product of the voltage and that component of the current that is in phase with the voltage. This is computed by taking the product of the voltage E, the current I, and the cosine of the angle of phase lag or lead, which is always equal to or less than 1.

By themselves, meters do little good. To be useful, they must be read, maintained, and their information organized for use. Many meters are now available with both direct readout capability as well as with a signal input to a digital processor for use in automatic data processing. This means that they may be ordered for use in a strictly manual operation, or for a highly automated system with central control, monitoring, and data processing.

METER TYPES AND THEIR CHARACTERISTICS

There are many different types of meters, each with its own special application advantages. None is perfect, and each choice represents a compromise involving cost, performance, and complexity. The following discussion is meant to introduce the reader to some of the more general characteristics of various types of meters. As the facility engineer investigates the facility's own special requirements and begins the process of obtaining detailed specifications and installation, operating, and maintenance information from manufacturers and users in the field, it will become much more clear what type of meter best meets the requirements of a particular application.

Condensate meter

This meter measures the volume of steam condensate. It consists of a drum designed to rotate as the condensate flows through it. Because it is mounted in the condensate line, installation does not need to interrupt service. It is regarded by users

as reliable, relatively simple to install, easy to maintain, and accurate (±0.5 to 1.0%). Accuracy is maintained at all flow rates from zero to the maximum rated. The cost of equipment and installation run between $300 and $3000.

Manufacturers include the Cadillac Meter Company, P.O. Box 1175, Port Townsend, Wash. 98368, (206) 385-5500.

Differential pressure—orifice plate

This meter is used for gas, liquid, or steam and is the most common type of steam meter used in direct line metering. It is mounted directly in the line, which must be shut down for installation or replacement. Because it is mounted directly in the line and gets its pressure differential by restricting the flow, it produces a large unrecovered pressure drop in the line. This in itself can be a costly operating factor and should be assessed. Accuracy is ±1 to 1.5% of maximum flow, and the meter is good down to flow rates only as low as 25% of maximum (turndown ratio of 4:1) or 10% (turndown ratio of 10:1) with a span adjustment. The cost of equipment and installation run between $2500 and $5500.

Manufacturers include the American Meter Co., Division of Singer, 1350 Philmont Ave., Philadelphia, Pa. 19116, (215) 673-2100.

Differential pressure—averaging Pitot tube

This meter may be used for gas, liquid, or steam. It may be installed either permanently or as an insertion type. As an insertion, it permits checking line flow periodically and using the same meter to check different lines of the same size. It does not sample the full stream flow. Dirty flow may clog probe openings. Its useful pressure range is about 2–10 in. of water with an accuracy estimated at ±1% of full scale. The turndown ratio is about 4:1 or up to 12:1 with a span adjustment. Line pressure drop due to the meter is low. The cost of equipment and installation is $2000 to $6000.

Manufacturers include Annubar, Ellison Instrument Division, Dieterich Standard Corporation, Boulder, Colo. 80302, (303) 449-9000.

Turbine-insertion type

This meter may be used for gas, liquid, or steam. It may be permanently or temporarily mounted. One size will measure several pipe sizes. Relatively simple maintenance may be required on the turbine every 1 or 1-1/2 years. The turndown ratio runs from 10:1 to 50:1. Flow straightness may be necessary, requiring straight pipe approximately 10 pipe diameters upstream and 4 diameters downstream from the turbine. It does not sample the full stream flow. The turbine blades are delicate and may be damaged by trash in the flow or by frequent startup. Turbine bearings may fail. Accuracy is approximately ±1% of reading. The cost of equipment and installation is $2000 to $6000.

Manufacturers include Engineering Measurements Co., 600 Diagonal Highway, Longmont, Colo. 80501, (303) 651-0550, and Electronic Flo-Meters Inc., P.O. Box 38269, Dallas, Texas 75238, (214) 349-1982.

Vortex shedding

The vortex shedding meter creates a disturbance in the flow and uses a sensor to measure the frequency of fluctuations in pressure produced by vortexes that occur at a rate proportional to the rate of flow. These pressure fluctuations are measured and translated to flow rate. The vortex shedding meter can be used in steam, liquid, or gas. Accuracy is reported to be ±1% of reading. The turndown ratio is from 8:1 to 30:1. Insertion models are under development. The cost of equipment and installation is estimated at between $1500 and $6000.

Manufacturers include: Eastech Inc., 26 West Highland Ave., Atlantic Island, N.H. 07716, (201) 291-3500; Fischer & Porter Co., County Line Road, Warminster, Pa. 18974, (215) 674-6000; Fisher Control Co., 205 South Center St., P.O. Box 190, Marshalltown, Iowa 50158, (515) 754-3011.

Target

This meter may require a straight run of pipe for 20 diameters upstream and 10 diameters downstream. It produces a low pressure drop and its turndown ratio is 10:1. It is used in difficult service applications such as viscous or dirty flow and for steam. Its accuracy is ±0.5% of full scale. The estimated cost of equipment and installation is $1500 to $3000.

Manufacturers include Hersey Products Inc., P.O. Box 4585, Spartanburg, S.C. 29305, (803) 578-1005.

Rotary shunt

The rotary shunt meter diverts part of the flow through a turbine. The rotation of the turbine is picked up magnetically and its rotational speed is proportional to the rate of flow. It is used for steam, air, or gas. Its turndown ratio is 10:1 to 60:1 and its accuracy is ±2% of reading. The estimated cost of equipment and installation is $1800 to $6000.

Manufacturers include: Cadillac Meter Company, P.O. Box 1175, Port Townsend, Wash. 98368, (206) 385-5500 or (800) 426-5611; Kent Process

Control, P.O. Box 6494, Edison, N.J. 08818, (201) 225-1717; BIF, 1600 Division Rd., West Warwick, R.I. 02910, (401) 885-1000.

Condensate return—run-time totalizer on condensate pump

This is similar to the condensate meter in that it measures steam flow by measuring the condensate, but it simply times the run time of the condensate pump. It requires that there be a condensate pump and that the flow characteristics of the pump be known (or measured in the system). Its accuracy is ±1% of reading and the estimated cost of equipment and installation is between $300 to $1500. This system would probably be facility-installed by purchasing a condensate pump (if needed) and a run-time totalizer.

Positive displacement water meters

These meters are positive displacement meters that use a magnetic pickup. They are made for hot, warm, and cold water measurements including boiler feed, condensate, and similar services. The accuracy is approximately 1% of reading. The estimated cost of equipment and installation is between $300 and $3000.

Manufacturers include: Kent Meter Sales, Inc., 903 N.E. Osceola, Ocala, Fla. 32670, (904) 732-4670; Neptune Water Meter Co., Box 458, Tallassee, Ala. 39078, (205) 283-6555; Hersey Products Inc., Hersey Measurement Co., P.O. Box 4585, 150 Venture Blvd., Spartanburg, S. C. 29305, (802) 574-8960.

Turbine water meter

This water meter is often used for larger sized pipes and flows. It consists of a turbine-driven shaft and a magnetic pickup. Accuracy is approximately ±2% of reading. The estimated cost for equipment and installation is $300 to $6000.

Manufacturers include: Kent Meter Sales, Inc., 903 N.E. Osceola, Ocala, Fla. 32670, (904) 732-4670; Hersey Products Inc., Hersey Measurement Co., P.O. Box 4585, 150 Venture Blvd., Spartanburg, S. C. 29305, (802) 574-8960.

Oil meters

Several types of oil meters are available for high temperature, high viscosity, multiviscosity flows, and a wide range of flow rates. Turndown ratios run from approximately 15:1 at an accuracy of ±1% to 100:1 at ±2%. These include oscillating piston and turbine meters. The estimated cost of equipment and installation is $100 to $2000.

Manufacturers include: Kent Meter Sales, Inc., 903 N.E. Osceola, Ocala, Fla. 32670, (904) 732-4670; Engineering Measurements Co., 600 Diagonal Highway, Longmont, Colo. 80501, (303) 651-0550; Electronic Flo-Meters, Inc., P.O. Box 38269, Dallas, Texas 75238, (214) 349-1982.

Gas meters

There are several gas meters in addition to the types cited above, including diaphragm, positive displacement, full-flow turbine, and orifice meters. These meters operate with an accuracy of approximately ±1% of capacity. Turndown ratios vary from 3:1 to 1000:1 depending on type and conditions. The estimated cost of equipment and installation is from $100 to $3000.

Manufacturers include: American Meter Co., Division of Singer, 1350 Philmont Ave., Philadelphia, Pa. 19116, (215) 673-2100; Rockwell International, Measurement and Control Division, 400 N. Lexington Ave., Pittsburgh, Pa. 15208, (412) 247-3000; Sprague Meter Co., 35 South Ave., Bridgeport, Conn. 06601, (203) 333-4172.

Electric meters

Electric meters measure kilowatt-hours, a unit of electrical energy. The industry-standard watt-hour meters, often referred to as wattmeters, take the power factor into account and measure real energy used. These meters totalize the electrical energy used and show their results on readout dials. They may be equipped with a digital impulse generator for demand metering and for information processing and central readout. Their accuracy is approximately 0.25% of readings. These meters are extremely reliable, with maintenance intervals of approximately 15 years. The estimated cost of equipment and installation is between $300 and $3000.

Manufacturers include: General Electric, Meter Business Department, 130 Main St., Somersworth, N.H. 03878, (603) 692-2100; Westinghouse Electric Corp., 2728 North Boulevard, Raleigh, N.C. 27611, (919) 834-5271; Landis and Gyr Metering Inc., P.O. Box 7180, Lafayette, Ind. 47903, (317) 742-1001.

Analog power meters

Analog watt transducers with both induction coil and Hall effect pickups are available. These are watt meters that provide a dc current or voltage output proportional to an ac power input and are corrected for power factor. They are totally electric and, unlike industry-standard watt-hour meters, have no moving parts. They can interface with an

energy management system microprocessor via an analog-to-digital converter, which should be located as close to the transducer as possible. Demand power readings are taken by sampling the wattage output from the transducer at 1-second intervals, and averaging over a 15-minute period. If the induction coil pickup type is used and it uses a split ferro-magnetic core sensor, it can be used on existing conductors without breaking into the line. Accuracy of these meters is about 1% of reading. The estimated cost of equipment and installation is $300 to $1000.

Manufacturers include: Yokogawa Corp. of America, 2 Dart Rd., Shenandoah, Ga. 30265, (404) 253-7000; Crompton Instruments, 2763 Old Higgins Rd., Elkgrove Village, Ill. 60007, (312) 593-1107; Weschler Co., 4000 Northwest 121st Ave., Coral Springs, Fla. 33065, (305) 755-7111.

Btu meters

This category is meant to include both simple and complex integrated systems that employ meters, electronics, and sometimes special equipment that allows the system to be moved from building to building. Some of these systems use microcomputers and some use simple analog devices. They are often designed to read out in terms of Btus of energy use. The cost can vary from $500 to $15,000 and up, depending on the type and application. This category is included to provide some reference to the electronic side of energy metering.

Manufacturers include: Foxboro/Adec Inc., 1421 E. Pomona St., Santa Ana, Calif. 92705, (714) 540-8863; Engineering Measurements Co., 600 Diagonal Highway, Longmont, Colo. 80501, (303) 651-0550; American Meter Co., Division of Singer, 1350 Philmont Ave., Philadelphia, Pa. 19116, (215) 673-2100.

Chapter 7. Stack Gas Analysis

The efficiency of furnaces and boilers is determined through stack gas analysis. Both portable and fixed equipment is available. Portable analyzers are used primarily for spot checks in small furnaces and boilers where the firing rate is fixed. They are often used to check the efficiency of combustion, to show what changes might be made to improve efficiency, and to check the result of changes after they are made. Fixed analyzers, on the other hand, are usually used in large boilers or process combustion systems where the firing rate may be variable or the process is so critical that precise control of conditions is required. Fixed analyzers are used both to provide the operator with continuous information on combustion system performance and to control the combustion process itself. Changing conditions in fuel heating value, viscosity, and temperature, along with variations in ambient air temperature and humidity, result in continuous changes in combustion conditions. These changes along with changing load conditions often make continuous monitoring and control cost-effective.

PORTABLE EQUIPMENT

There are two commonly used types of portable stack gas analysis systems. One is the Orsat "dumbell" system and the other is an electronic analyzer. Both show approximately equivalent accuracies. Accuracy on overall combustion efficiency is not usually given by the manufacturers because there are too many factors in the computation of efficiency. However, the O_2 (oxygen) measurement accuracy is about ±0.5% O_2 for both systems. If the reading were 3% O_2, a tolerance of ±0.5% O_2 would be ±17% measurement error. For this reason, it is usually recommended that several Orsat readings be taken and averaged.

The Orsat "dumbell" system uses chemical CO_2 or O_2 analysis, stack gas temperature probe, and a smoke tester or CO measurement depending on whether the fuel is oil or gas. With the information derived from this analysis, the efficiency of the combustion and heat exchange process can be determined. Some skill and experience is required to take the measurements and make the calculations necessary to determine combustion efficiency.

Costs for complete combustion analysis kits run from $250 to $500. The Bacharach Instrument Co., 625 Alpha Drive, Pittsburgh, Pa. 15238, (412) 963-2000, is the only U.S. producer of the Orsat "dumbell" system.

Electronic analyzers have the advantage of being easier to operate than the Orsat system and, as a result, might be considered more accurate, although in skilled hands the Orsat system has the capability of roughly equivalent accuracy. The portable electronic stack gas analysis measures the stack gas parameters and uses a microprocessor to make its calculations. It has a digital readout. Two types are available. One is for individual readouts and ranges in cost from $400 to $700. The other is designed to measure continuously over a short period, say 15 minutes, to allow continuous monitoring of efficiency while adjustments are made and conditions change in an industrial boiler. The cost of these systems ranges from $1800 to $3000.

Manufacturers include the Bacharach Instrument Co. of Pittsburgh, Pa. (412) 963-2000; Teledyne Corp. of San Gabriel, Calif. (213) 283-7181; and Lynn Products Co. of Lynn, Mass. (617) 593-2500.

FIXED EQUIPMENT

The two basic types of fixed systems for stack gas analysis are in-situ and extractive. Both use a zirconium oxide cell coated on both sides with porous platinum. One side of the cell is exposed to air and the other to the stack gas. When heated to about 1200°F (650°C) the cell causes oxygen molecules coming in contact with the platinum to pick up four extra electrons, and when there is a difference in the oxygen partial pressures between the two sides of the cell, there is a flow of oxygen molecules from the high- to the low-pressure side. Because these molecules are ionized, a voltage difference between the two sides is established that is proportional to the difference in oxygen partial pressure between the air and the flue gas. From this voltage difference, the oxygen content of the flue gas is calculated.

An excellent booklet, *Flue Gas Measurement—A Guide to Maximizing Combustion Efficiency*, is available from Ametek, Thermox Instruments Division, 150 Freeport Rd., Pittsburgh, Pa. 15238.

In-situ systems

The in-situ system utilizes a probe with a small zirconium oxide cell that includes a filter for the

stack gas and a supply of clean dry instrument air supplied through the probe. Maximum stack gas temperature allowable for the in-situ analyzer is about 1100°F (593°C), which permits its use in most boiler/furnace applications. Exceptions would be special-process applications where very high stack gas temperatures may be required.

The life expectancy of an in-situ zirconium oxide cell is from 1 to 5 years, depending on the corrosiveness of the stack gas constituents. Calibration should be done every 1 or 2 months on a general-purpose boiler and as often as every week if used on a critical process. All in-situ probes should employ flame arrestors so that, in the event of a burner malfunction producing a fuel/air mixture in the stack, the heated zirconium oxide cell will not cause an explosion. Accuracy of the in-situ system is about ±6% of the reading. The cost of an in-situ system is $2700 to $4000.

Electronics connections to the in-situ probe are limited to a maximum of about 20 ft.

Extraction systems

Although the principles of operation of the in-situ and extraction analyzers are the same, the extraction system extracts a stack gas sample and removes it to a large zirconium oxide cell outside the stack. This system permits its use with stack gas temperatures up to 3200°F (1760°C) and, because the cell is larger and produces a stronger signal, the electronics of the system may be located farther away than is possible with the in-situ system. In addition, extraction system analyzers are available that can measure carbon monoxide and hydrogen combustibles.

Calibration requirements are about the same for in-situ and extraction systems. The accuracy of the extraction systems is ±2% of the measured value. It is perhaps more important that the repeatability of readings for an extraction system can be excellent, with variations between readings of less than 1%, whereas the in-situ system readings, because of the varying flue gas conditions, can show variations up to 5 or 6%.

The cost of an extractive O_2 analyzer varies from about $3000 to $7000. The cost of an extractive O_2 plus combustibles (CO and H_2) analyzer varies from $4000 to $8000.

Manufacturers of in-situ and extraction analyzers include Thermox Instruments Division of Ametek, Westinghouse Combustion Controls Division, Bailey Division of Babcock and Wilcox, and Cleveland Controls.

Chapter 8. Energy Management and Control Systems (EMCS)

Energy management and control systems (EMCSs) can be used for both energy and maintenance management. Most EMCSs employ off-the-shelf minicomputer/microcomputers, instrumentation, and equipment configured into a network with control monitoring functions at multiple locations for heating, ventilating, air conditioning, process equipment, lighting, chillers, and boilers.

The capacity of an EMCS to effect energy savings and optimize energy use will depend on the number, type, and location of sensing and control points as well as on the type of equipment and controls being managed.

Many energy-using systems in our current building inventory were originally designed and operated with little concern for energy conservation. EMCSs were extensively employed in the late 1970s as a means of reducing energy usage in fundamentally inefficient systems. In many cases these EMCSs were able to assist in reducing energy costs by as much as 40%. They accomplished this in several ways:

1. Duty Cycling—The EMCS starts and stops HVAC equipment based on a preset schedule to reduce unnecessary run times on electric motors that drive blowers, chillers, and pumps, and on other energy-consuming HVAC equipment.
2. Central Sensor Temperature Control and Night Set-Back—The EMCS turns an HVAC system on or off to satisfy a centrally located sensor positioned to provide approximately average temperatures in the area the system serves. This removes control from the hands of individual users who may not observe the required maximum heating or minimum air-conditioning temperature established by the government or agency in control. The EMCS can usually be programmed to use different temperatures for night or long-term shutdown. In cold regions, to avoid freeze-ups, it is important to place sensors for long-term shutdown (where 45°F or 50°F might be used to save energy) in locations expected to be the coldest. This is often difficult, as the coldest location in a building depends on wind speed and direction. More than one sensor is often used for this type of low-temperature control, and the system is designed to respond to the sensor exhibiting the lowest temperature. Building occupants cannot adjust these sensors as they might a thermostat. The control function remains in the EMCS and is adjustable only from the central or local control console.
3. Demand Limiting—The EMCS selectively shuts down users of electricity to keep total momentary electric usage from exceeding a pre-established peak above which the facility will be assessed a rate penalty by the utility.
4. Monitoring and Alarming—The EMCS monitors space temperatures and equipment operation and alarms the central control operator when preset values are exceeded or critical equipment fails. This saves energy when a failed system would tend to increase temperatures or cause systems to run unnecessarily.
5. Monitoring Motor Run Time—The EMCS monitors and records run time on electric motors. This can provide information necessary to determine potential cost savings and payback for replacing existing motors with new high-efficiency motors.
6. Controlling Motor Stop/Start Times—The EMCS avoids too close stop/start cycling, which can significantly reduce motor life. This would result in maintenance cost savings.

One of the most difficult problems in attempting to make existing HVAC equipment energy-efficient is that the controls used, particularly the most prevalent pneumatic controls, are not precise, are difficult if not impossible to keep calibrated, and consequently are prone to out-of-balance operation. Most controls in existing buildings were designed when energy costs were very low and when HVAC systems were designed to heat and cool at the same time. During times of relatively low-cost energy, reheating cooled air to get proper room temperature was common. Today, except where significant dehumidification is required, reheat systems are seldom used. As energy conservation became important, some of the greatest savings were realized as a result of changing the operation of building HVAC systems to keep them from reheating previously cooled air—from heating and cooling at the same time. This required a finer control function, however, which most controls and most systems were not able to provide. As a result, much time and effort has gone into adjusting and maintaining controls; even with increased

maintenance, complex buildings modified in operation to be energy-conserving often do not function very well, at least not to the satisfaction of many of the users. Thus, the ability of EMCS to provide both energy savings and user satisfaction depends a great deal on the HVAC equipment, the system control design, the way the EMCS is integrated into the system, and the types of sensors and controls the EMCS integrates.

The heart of an EMCS is a digital computer fed by analog sensors that control certain HVAC system functions. The quality of the information available to the energy manager is a function of sensor accuracy and reliability, sensor location, and the choice of measured system parameters. The ability to minimize energy use while still providing user comfort and utility depends on the quality of information fed to the EMCS, the inherent ability of the HVAC system to modulate its energy usage, and the characteristics of the EMCS-HVAC control linkages.

Both the sensing and the control portions of an EMCS are crucial to its ability to help the energy manager conserve energy. At the present time most EMCSs do not employ energy-flow sensing. They measure temperature and sometimes pressure but almost never flow. Thus, a current EMCS will not give an energy manager all that is required to measure actual energy consumption. The energy manager can use the EMCS to reduce energy usage by controlling blower run times, assuring against over-temperature operation, and employing other techniques made available by having an EMCS monitor energy-related system parameters. The manager knows that if temperature in a heated building is reduced 5°F, or increased 5°F in an air-conditioned building, the building energy usage will drop. At present, however, most EMCSs will not actually monitor the energy flow, and the manager only receives this information indirectly by reading steam or electric meters or waiting for the utility bill.

HVAC control technology is gradually changing. The development of digital controls is underway and some have been used by innovative users of complex systems. Several manufacturers are producing or are about to produce direct digital control (DDC) systems. DDC systems promise accuracy and reliability. Resistance to their development has been due both to inertia on the part of the large control manufacturers and to cost. Often first cost is what controls building equipment decisions. Life-cycle costs, which would include energy use, are more often talked about than used, both inside and outside the government, and when energy costing is used outside the government, 1- to 3-year energy paybacks on equipment are usually required. In nongovernment retrofit, where energy payback is most often used, a short 1- to 3-year payback predominates. Thus the development of accurate HVAC controls has been slow.

To employ an EMCS successfully, the facility engineer may wish to consider the following steps:

1. Identify and understand the important energy-using systems within the facility. Complex buildings and the major energy users within them must be identified.
2. Evaluate the existing controls and determine their characteristics and capabilities, since an EMCS is limited by local controls on energy-using equipment. Determine the ability of existing controls to maintain calibration.
3. Consider what is needed to upgrade control and HVAC equipment components to provide satisfactory control and operation and to provide a system that integrates well with candidate EMCSs.
4. Determine what information is needed to monitor and manage energy use.
5. Determine the number, location, and type of sensing devices needed to provide the necessary information.
6. Estimate the growth potential of individual buildings and the potential for new facilities. Identify potential changes and estimate additional servicing points that might be required over the next 10 years.
7. Investigate EMCS candidates to determine which types fit the needs of the facility. Provide potential EMCS suppliers with your detailed needs and work with EMCS manufacturer specifications to optimize system utility. Verify that the EMCS has the capacity to monitor all sensing points and enough room for anticipated expansion. Keep in mind the need for flexibility and the possibility of incorporating new components as technology changes. Energy managers usually find out a great deal more about their equipment *after* the EMCS has been installed: as more is understood, more is seen that may need to be changed, so system flexibility is important.
8. For large or complex installations, it is very useful to simulate equipment operation on the EMCS. This allows the EMCS manager to program the characteristics of various HVAC systems and see what result a change in operating parameters will have in system operation. Without the simulation capability, the EMCS manager will have to make changes

using the HVAC systems and then watch the results. What can take days and significant amounts of energy using the actual HVAC systems in real time takes only a few minutes with simulated runs.

9. Consider a distributed vs a centralized EMCS. A large facility with several complex energy-using buildings may prefer a distributed control system. Distributed processing allows for varying amounts of programming and spot monitoring at the distributed field locations. The heart of the distributed control concept is the intelligent field interface device or "smart FID" ("smart" because each device can continue performing energy-management functions if the central unit or any FID in the network fails). As distributed control becomes better developed, it allows the use of more units networked together with the ability to exchange information between controllers without going through the central computer.

Although EMCS was originally used as a central monitoring system with limited control functions, its use as a controller is now expanding significantly. The new digital control technology initiated by EMCS has placed increased emphasis on direct digital control (DDC). These controls combine a microprocessor with sensors and electric actuators and represent a new controls technology alternative to the old pneumatic thermostats, receiver/controllers, and activators. DDC has several advantages over the old pneumatic controls:

- It creates more accurate and sophisticated control.
- It reduces maintenance due to fewer parts, greatly reduced calibration requirements, and the avoidance of a complex compressor-driven pneumatic system that is prone to compressor oil contamination.
- Lower building life-cycle cost.
- The ability to communicate directly with the EMCS.

The last item above opens the door to using the EMCS with DDC as an energy-flow measuring device since, if the flow characteristics of water, steam, or air duct valves and dampers used for heating or cooling are known and are part of the EMCS algorithms, the DDC can provide feedback to the EMCS on valve or damper position and flow temperature, velocity, and pressure to provide energy flow information for use in allocating energy use to specific areas.

As of 1986, DDC had a higher initial cost than pneumatic systems and was relatively new in the marketplace, with a limited number of suppliers. However, the number of suppliers is increasing; several were to release new DDC equipment in 1986. The cost of DDC equipment is likely to come down as usage increases.

The cost of EMCSs varies widely depending on size and complexity.

An extensive list of EMCS suppliers can be found in *Energy User News* (1986). An updated version of this list is included below.

List of EMCS Suppliers
(Updated by *Energy User News* in 1988)

Aegis Energy Systems, 607 Airport Blvd., Doylestown, Pa. 18901

AET Systems, 77 Accord Park Drive, P. O. Box C, Norwell, Mass. 02061

Alerton Technologies, Inc., 1525 131st Ave. N.E., Bellevue, Wash. 98005

American Auto-Matrix, 1 Technology Drive, Export, Pa. 15632

Anderson Cornelius Co., 6750 Shady Oak Road, Eden Prairie, Minn. 55344

Andover Controls Corp., York and Haverhill Streets, Andover, Mass. 01810

Automated Logic Corp., 1283 Kennestone Circle, Marietta, Ga. 30066

Barber-Colman Co., 1354 Clifford Ave., Loves Park, Ill. 61132

Barrington Systems, 1160 Industrial Road, San Carlos, Calif. 94070

Cetek Systems Inc., 1701 Junction Court, San Jose, Calif. 95112

Computer Controls Corp., 54 Industrial Way, Wilmington, Mass. 01887

Control Pak Corp., 23840 Industrial Park Drive, Farmington Hills, Mich. 48024

Control Systems International, P. O. Box 59469, Dallas, Texas 75229

EIL Instruments Inc., 10 Loveton Circle, Sparks, Md. 21152

Electronic Systems USA, 1014 East Broadway, Louisville, Ky. 40204

Encon Systems Inc., 502-F Van Dell Way, Campbell, Calif. 95008

Enercon Data Corp., 7464 West 78th St., Minneapolis, Minn. 55435

Functional Devices Inc., 310 South Union St., Russiaville, Ind. 46979

General Electric Co., Wiring Device Dept., 225 Service Ave., Warwick, R. I. 02886

Honeywell Commercial Buildings Group, Honeywell Inc., Honeywell Plaza, Minneapolis, Minn. 55408

Honeywell Building Controls Division, 1985 Douglas Drive N., Golden Valley, Minn. 55422-3992

Honeywell Building Controls Division, Albuquerque Systems, Honeywell Inc., 8500 Bluewater N. W., Albuquerque, N. M. 87105

HSQ Technology, 1435 Huntington Ave., South San Francisco, Calif. 94083-2248

Hypertek Inc., Salem Industrial Park, P. O. Box 137, Route 22 East, Whitehouse, N. J. 08888

IBM Corp., Dept. 805, 1133 Westchester Ave., White Plains, N.Y. 10604

IDMA/Climatron Inc., 1041 S. Placentia Ave., Fullerton, Calif. 92631

Intermatic Inc., Intermatic Plaza, Spring Grove, Ill. 60081

Jade Controls, P. O. Box 271, Montclair, Calif. 91763

Johnson Controls Inc., 507 East Michigan St., Milwaukee, Wisc. 53202

Lumenite Electronic Co., 2331 North 17th Ave., Franklin Park, Ill. 60131

Landix & Gyr Powers, 1000 Deerfield Pkwy., Buffalo Grove, N.Y. 60015

MicroControl Systems Inc., 6589 North Sidney Place, Milwaukee, Wisc. 53209

Novar Controls Corp., 24 Brown St., Barberton, Ohio 44203

Paragon Electric Co. Inc., 606 Parkway Blvd., P. O. Box 28, Two Rivers, Wisc. 54241

Powerline Communications Inc., 123 Industrial Ave., Williston, Vt. 05495

Robertshaw Controls Co., Integrated Systems Div., 3000 D South Highland Drive, Las Vegas, Nev. 89109

Robertshaw Controls Co., Control Systems Div., P. O. Box 27606, Richmond, Va. 23261

Sachs Energy Management Systems Inc., P. O. Box 96, St. Louis, Mo. 63166

Scientific Atlanta, 4300 Northeast Expressway, Atlanta, Ga. 30340

Solid State Systems Inc., 1300 Shiloh Road, N.W., Kennesaw, Ga. 30144

Solidyne Corp., 1202 Carnegie St., Rolling Meadows, Ill. 60008

Staefa Control System Inc., 8515 Miraslini Drive, San Diego, Calif. 92126

TJ Controls Inc., 406 North Union St., Bryan, Ohio 43506

Tork, 1 Grove St., Mt. Vernon, N.Y. 10550

Towne Applied Technology, Inc., 685 Howard St., Buffalo, N.Y. 14026

The Trane Co., 5301 East River Road, Minneapolis, Minn. 55421

Triangle Microsystems Inc., 2716 Discovery Drive, Raleigh, N.C. 27604

Tropic-Kool Engineering Corp., 129000 Automobile Blvd., Clearwater, Fla. 33520

This list includes all firms known to *Energy User News* at the time of publication. It should not be construed as complete. This list of energy management system suppliers includes only companies that put their names on the equipment they sell. It does not include distributors or dealers.

Chapter 9. Lighting System Evaluation

MEASUREMENT AND ANALYSIS

One of the most widely used devices for measuring light is the selenium cell. Coupled with a microammeter, corrected filters, and multirange switches, this cell is used in hand-held light meters and other more precise instruments. For multirange use in precision meters, different cell heads are used. Cadmium sulfide photocells, in which the resistance varies with the illumination, are also used in light meters.

The small survey-type meters do not have the accuracy of lab-oratory meters, and readings should be considered approximate, although they may be quite consistent for a given condition. Their range is usually from about 5 to 5000 footcandles. Precision low-level meters have cell heads with ranges down to 0 to 2 footcandles.

If light meters are used to measure the number of lumens per square foot leaving a surface, foot lamberts (brightness) instead of footcandles (illumination) are being measured. Light meters can be used to measure brightness, but electronic brightness meters containing a phototube, amplifier, and microammeter can read brightness more directly. Typical ranges are from 0.0001 to 100×10^6 foot lamberts on a single meter.

Light meters that incorporate a spherical diffuser can be used to measure incident light on a surface. For a reflected light measurement the meter is pointed toward the subject without the diffuser over the photo cell. Usually light meters are used in walk-through type lighting audits of a building where both natural light from windows and artificial illumination from lighting fixtures can be measured. The measured light levels are then compared with standardized levels and recommendations are made with respect to effective cost reduction.

ACCURACY

Not available.

ADVANTAGES

Light meters can be used to measure the combined illumination in a space that results from natural light (windows) as well as from artificial light (lighting fixtures). They can also be used to measure the actual illumination in situations where the measurement would be preferable to the calculated value (e.g. reduced illumination due to soiled bulbs).

Multipoint lighting analysis is required for a true picture of light levels. This requires a great deal of time, or multiple sensors if many tests are to be run. Measurement of equivalent sphere illumination, one measure of lighting effectiveness, requires a special overlay for the light meter and a computer analysis of the data. Light-measuring equipment can be expensive, depending on accuracy and complexity.

Using measured bright levels, it is possible to get a more accurate level of lighting availability than using the technique of adding the total electrical input (watts) to all the lighting fixtures in a space and dividing by the illuminated area of the space. The measured light levels take into consideration the availability of natural light as well as the actual light levels incident upon individual work surfaces (tables, desks, computer terminals, etc.).

LIMITATIONS

Measuring light levels is more time-consuming than a walk-through audit based on calculations.

NEW TECHNOLOGY/DEVELOPMENTS

Light meters are available that incorporate a memory for storing light values, instantaneous readings, programmable exposure changes, a spherical diffuser for incident footcandle readings, and various other accessories.

Using a portable computer terminal, results of a walk-through lighting audit can be processed onsite by keying all data in to a central computer over telephone lines. Such data includes but is not limited to heating and air-conditioning costs, type of fuel, number of lamps, mounting height of lamps, lamp life and usage, maintenance and installation costs, and lighted areas.

COST

Depending upon complexity, the cost can range from $25 to $200.

Chapter 10. Electrical System Evaluation—Meters (Volt, Amp, Watt, Ohm)

MEASUREMENT AND ANALYSIS

Over a period of about 150 years many persons have contributed to the art of measuring electrical quantities, such as volts, amperes, and ohms. Through most of this period of history the principal effort of making instruments react to electricity was aimed at the perfection of pointer-deflecting instruments. In these, the deflection angle of the pointer is proportional to the value of the electrical quantity measured. The name "analog instruments" has been coined to distinguish these instruments from a completely different type in which the value of the quantity measured is displayed in numerals. These newer instruments are called digital instruments. Digital electrical instruments owe their existence to the ability of electronic devices to create electrical pulses, perform rapid switching operations, produce precisely predictable time functions of voltage, make voltage comparisons, amplify, and perform the fundamental operations of addition, multiplication, differentiation, and integration. The distinction between analog and digital instruments is perhaps less significant than the basic approach to electrical measurements. Just as we weigh objects against a standard weight on a calibrated spring, so we can measure electrical quantities such as voltage or current by balancing the torque they produce in an electromagnetic system against a calibrated spring, or we can balance the electrical quantity itself against a standard value of that quantity, as in a potentiometric system.

Styling of analog instruments has produced a multiple-range, tabletop instrument that contains a permanent-magnet, moving-coil mechanism with a variety of circuits and transducers for measuring many electrical functions in one modular housing. With a permanent-magnet, moving-coil mechanism, this instrument measures direct current and voltage; with a moving iron vane mechanism, it measures alternating current and voltage.

A digital voltmeter converts the analog input into digital logic and displays it in decimal form. Solid-state electronics perform many functions at high speed and with great accuracy. Digital instruments use electrical and electronic means to convert electrical quantities into digital outputs and readings. Almost always the input quantity is a voltage, since other quantities are easily converted into voltage before they are processed by the instrument.

ACCURACY

Electrical instruments may be calibrated against the primary standards of the quantity measured. However, most are calibrated against secondary standards whose calibrations are traceable to the primary standards. All primary standards in the United States are established and maintained by the National Bureau of Standards.

Alternating current voltmeters and ammeters are usually calibrated against electrodynamic voltmeters and ammeters that have been calibrated on direct current and have a known accuracy on alternating current. The finest analog instruments are rated to be accurate to within ±0.1% of full scale. Digital instruments can be made 50 to 100 times more accurate.

ADVANTAGES/LIMITATIONS

The comparative rate of change of the quantity measured can be judged more easily when observing the motion of a pointer on an analog meter than a change in the value of a digital readout. Analog instruments are preferred when a visual indication of rate is important.

Analog instruments are relatively simple in construction and can be made to perform under very unfavorable environmental conditions, but they contain moving parts.

Digital instruments are relatively complex and made of parts and components whose reaction to environmental conditions varies. However, digital instruments can be made without moving parts.

Diagnostic electrical measuring meters are relatively inexpensive and extensive training is not required for their proper use.

NEW TECHNOLOGY/DEVELOPMENTS

Meters are being manufactured that will communicate directly with a computer. The use of thermal scanning techniques to determine the temperature rise in an electrical conductor is a relatively recent development and is worth describing in detail.

Failure mechanisms in current-carrying equipment usually develop as a result of overheating, caused by high-resistance connections of circuit conductors. Overheating causes the deterioration

of electrical and mechanical components as well as the insulation. Factors that contribute to the formation of high-resistance connections include loose connections, improper equipment design and installation, vibration, expansion and contraction of circuit parts due to load cycling, deterioration of mechanical components, and oxidation of conducting surfaces. Overheating of high-resistance connections is a self-compounding problem. The temperature increases with the resistance of the connection. The greater the temperature rise the more pronounced the effects of forces that further increase the resistance. The problem becomes progressively worse until a failure causes a short circuit that damages or destroys the device. Using a thermal imager the resistance of circuit connections can be checked by evaluating the thermal image of the device's terminals. Temperature differences between various locations in a terminal can be measured with a differential-temperature-measuring imager. Note that if the imager does not have the capacity to measure temperature differentials, only qualitative comparisons (intensity differences of bright locations) can be obtained.

The basic method in the inspection of electrical/mechanical components is to observe the thermal operating characteristics of the equipment to discern if any abnormalities exist. Any abnormalities can be analyzed to determine the severity and the cause of the problem. Three comparisons can be made with a thermal imager to observe the operating characteristics of an electrical device: parts of the device can be compared with itself, with an adjacent device, or with the ambient air temperature. Each comparison provides a different reference for obtaining an overview of the operating conditions. The speed at which the inspection is performed will depend on several factors, including the complexity of the electrical/mechanical equipment, the operator's skill and technique in operating the thermal imager, and the number and nature of the problems that are detected. Simple distribution equipment can usually be inspected in a few seconds; more complex apparatus may take several minutes. Since some circuit components normally operate hotter than ambient temperature, thermal patterns can be very complex. Experience and knowledge of electrical equipment and distribution systems are very important to the results of an inspection.

When a problem is detected, a more detailed summary is done to pinpoint the location and to analyze the nature of the problem. Photographs and thermograms are taken to record both the thermal data and the visual scene. Notes are taken to record the information necessary to identify the location and describe the nature of the problem. These notes are used later in the preparation of a written report.

There are some failure mechanisms inherent in current-carrying equipment that are indicated by "cold spots." As mentioned earlier, some electrical devices normally operate much hotter than ambient temperature. If these are observed to be operating at ambient or colder than normal temperatures, a problem is indicated. There are failure mechanisms other than high-resistance connections that show up as hot spots. A severely unbalanced condition could cause the failure of a motor, generator, or transformer. Unbalanced currents in a three-phase system can also be detected. The temperature of the conductors that are carrying more current will be higher than those carrying less current. In this situation, the imager will indicate two phases that are operating at equally higher temperatures than the third phase. This indication of an unbalanced current can be confirmed by measuring the currents flowing in each phase with a clamp-on ammeter.

A good electrical connection is characterized by very low resistance. A low-resistance ohmmeter can be used to measure the resistance of circuit connections, but the circuit must be de-energized. It would be very time-consuming to measure the resistance of every connection in an electrical system, and it is usually difficult to schedule a power shutdown for that purpose.

A quantitative thermal imager can be used for remote and rapid monitoring of the relative apparent temperatures of all conducting/insulating surfaces without disrupting normal system operations. With this information, priorities can be assigned to the repairs that are needed.

Note that a nonquantitative imager can only be used to make a qualitative comparison (extremely hot, hot, warm, not hot) between two or more conducting/insulating surfaces.

If true temperatures are required of a conducting/insulating surface, then system calibration curves and surface emittances are required. This procedure requires somewhat more time and effort than that required for differential measurements.

COST

Depending upon the accuracy desired, the cost can range from $25 to several hundred dollars.

Chapter 11. Indoor Air Quality Measurements

CARBON MONOXIDE (CO) MONITOR

Measurement and analysis

Although long-term health effects from exposure to low levels of CO are suspected, exposure to high levels of CO for a shorter period of time can cause more serious immediate health problems, including death. Typically, CO levels high enough to cause "short-term" health effects are generated by a blocked combustion flue, a faulty or poorly tuned combustion source, or a car with its engine on in a garage. There are several commercially available continuous real-time monitors that can reliably measure CO levels through an electrochemical oxidation/diffusion process. Indoor CO problems can be detected by turning on the combustion sources for a specified time interval and measuring the CO levels.

An alternative to monitoring the continuous CO concentration is to measure the average CO levels over a longer period of time. From the long-term CO concentrations it should be possible to identify a residence that has high intermittent CO levels. In general, a home with a higher average CO concentration will have high CO peaks. One approach is to use a passive monitor that requires no external power and usually measures an integrated pollutant concentration over a period of 24 hours to 7 days. One passive technique available is to expose a tube of silica gel beads impregnated with potassium pallado sulfite (PPS), which changes color from yellow to brown in the presence of CO.

Accuracy

Active: From ±1 to ±15%.
Passive: From ±2 to ±5%.

Advantages

No training is required for either the active or passive sampling operation. The real-time monitor data do not require laboratory analysis, and the results can be made available immediately.

Limitations

The field reliability and accuracy of PPS indicators for spot or average measurements in a large-scale audit have not been established. For spot measurements, there is no guarantee that a single measurement is representative of normal furnace, stove, or other combustion activities. For average measurements, the diffusion characteristics of CO through silica gel beads are not adequately defined to make quantitative measurements.

New technology/developments

None.

Cost

Active: From $1700 to $2500.
Passive: From $700 to $1400.
Potassium pallado sulfite (PPS) beads for passive sampling cost $1.50 per tube in lots of 1000.

FIBROUS AEROSOL MONITOR

Measurement and analysis

Sample air passes through a chamber and enters a sensing region illuminated with a He-Ne laser. The light scattered out of the laser beam by the oscillating fibrous aerosols is detected by a photomultiplier tube.

Accuracy

The accuracy is equal to reproducibility when the monitor is calibrated for specific fibers.

Advantages

The monitor can operate unattended for an indefinite period of time. It may be operated off a battery pack and has recorder output. A standard membrane filter permits concurrent collection of fiber samples.

Limitations

The monitor requires occasional cleaning of the optics.

New technology/developments

None.

Cost

$12,000 to $13,000 with battery pack and digital-to-analog interface.

FORMALDEHYDE (HCHO) MONITORS

Measurement and analysis

The principle of operation of the active formaldehyde analyzer is that sample air is drawn through a solution that contains a fixed quantity of sodium sulfite. After the addition of pararosaniline the intensity of the color in the yellow part of the spectrum is measured.

Passive formaldehyde monitors operate by a process where the formaldehyde diffuses into the monitor and is collected by a sorption process. They can be left unattended from 2 hours to approximately 1 week. The shelf life of these devices ranges from a few weeks to approximately 1 year, depending on whether or not they have been previously exposed to formaldehyde.

Accuracy

Active: ±3%.

Passive: ±13 to ±25%.

Advantages and limitations

Active

98% collection efficiency. Can be used over a range of 5 to 95% relative humidity. No training is required for sampling.

Passive

Requires no power and no specialized training. It provides low accuracy and low reproducibility, but it is inexpensive. Laboratory analysis must be used to obtain quantitative results.

New technology/developments

None.

Cost

Active

$5000 to $6000.

Passive

From $7 to $35 depending on lot size and analysis requirements.

PARTICULATE MONITOR (ACTIVE/PASSIVE)

Measurement and analysis

A pulsed infrared laser, in combination with a detector, senses the forward light scattered by the particulate matter. In the passive device the air flows freely, while the active device uses a pump to pull the air through the sensing volume.

Accuracy

The accuracy is equal to the reproducibility for specific aerosols.

Advantages

The particulate monitor can be operated over a humidity range from 0 to 95%. No training is required for sampling.

New technology/developments

None.

Cost

Passive

Approximately $2000 without a recorder.

Active

From $6500 to 8000 without a recorder.

PARTICULATE SAMPLER/IMPACTOR

Measurement and analysis

Air is accelerated through nozzles or slots designed to pass or reject particles of various sizes. The particles are then collected and analyzed.

Accuracy

Accuracy is specified at certain flow rates and pressure drops and varies between ±3% and ±10%.

Advantages/limitations

The instrument will sample any ambient particulate concentration. Training is required.

PARTICULATE ANALYZER

Measurement and analysis

The sample air stream is passed through an impactor to remove nonrespirable particles. The particles that exit the impactor are precipitated onto an oscillatory quartz crystal sensor. The change in frequency of the sensor is proportional to the particulate mass that has collected there.

Accuracy

The accuracy is ±10%–0.01 mg/m^3.

Advantages

The particulate analyzer provides relatively high collection efficiency. No training is required for sampling.

Limitations

Annual calibration is recommended and main-

tenance is required. Changes in relative humidity during a measurement can cause error. Some particles (e.g. dry diesel exhaust) are not sensed accurately.

New technology/developments
None.

Cost
From $5000 to $17,000, depending upon the model.

NITROGEN DIOXIDE (NO_2) ANALYZERS (ACTIVE)

Measurement and analysis
The principle of operation of one analyzer is based on a chemiluminescent reaction with ozone that is detected by a photomultiplier tube. Another analyzer uses a dye-forming reagent to continuously absorb the sample air. The intensity of the dye is measured at a specific wavelength in the yellow spectrum to obtain the NO_2 concentration.

Accuracy
Instrument accuracy is dependent upon the accuracy of the calibration source.

Advantages
Training is not required. Both analyzers can be used over a wide range of humidity (5–95%).

New technology/developments
None.

Cost
Chemiluminescent: $7300 (without recorder and battery pack).
Chemistry/colorimetry: $5800.

NITROGEN DIOXIDE (NO_2) SAMPLERS (PASSIVE)

Measurement and analysis
The basic principle of operation in three commercially available devices is diffusion/sorption. In the dosimeter the collection relies upon molecular diffusion to deliver sample air to a liquid sorbent solution at a constant rate. After exposure the sorbent is analyzed in a laboratory spectrophotometer. In the Palmes tube the cap is removed during sampling and NO_2 diffuses to a collector at a rate determined by the tube geometry and ambient NO_2 concentration. At the termination of the sampling period the collector substrate is analyzed to obtain a quantitative value for the time-weighted average concentration. The NO_2 filter badge basically uses the same principle of operation as the Palmes tube.

Accuracy
The instrument accuracy is from ±18 to ±20%.

Advantages
No training is required for sampling, and no maintenance is required.

New technology/developments
None.

Cost

Device	Amount
Dosimeter	Approx. $1.00 ea. in lots of 260 or more
Palmes tube	$8.00 to $10.00 each
Filter badge	$11.65 each

OZONE METER

Measurement and analysis
The basic principle of operation is the photometric detection of the flameless reaction of ethylene gas with ozone.

Accuracy
Not available.

Limitations
Training is recommended.

New technology/developments
None.

Cost
The cost is about $6000 to $7000.

RADON COLLECTOR (PASSIVE)

Measurement and analysis
Ambient radon diffuses into a chamber where the subsequent disintegration of particles is electrostatically focused onto a dosimeter chip. Each particle striking the chip creates defects that can be related to the integrated radon concentration. The instrument is based upon the passive environmental radon monitor.

Accuracy
Not available.

Advantages
The passive radon collector can operate up to 1 year unattended, and it can operate over a wide range of ambient temperatures and humidity. No training is required for sampling.

New technology/developments
None.

Cost
$600 (includes batteries).

RADON MONITOR (ACTIVE)

Measurement and analysis
Radon daughters are collected on a filter and particle activity is measured with a detector. A microprocessor counts and stores detector pulses.

Accuracy
Typical accuracy is ±5%.

Limitations
The active radon collector requires some maintenance. No training is required for sampling.

New technology/developments
None.

Cost
$2000 to $3000, depending upon the model.

RADON/RADON DAUGHTER DETECTOR (ACTIVE)

Measurement and analysis
A known volume of sample air is drawn through a filter and a gas scintillation cell. Radon daughter products collect in the filter while the gas cell retains a sample of radon.

Accuracy
Not available.

Advantages
The instrument is usable over a wide ambient temperature range.

New technology/developments
None.

Cost
Approximately $8000 with optional accessories.

RADON GAS MONITOR (ACTIVE)

Measurement and Analysis
The active radon monitor has three measuring ranges and selectable sampling intervals. It contains a sample chamber, solid-state detectors, and a microprocessor to control operation. Ambient air is drawn through a prefilter that collects daughter products of two radon isotopes. Air enters a sample chamber and the decay particles are deposited on a solid-state detector. The decay particles are analyzed to discriminate between the two radon isotopes. Daughter products captured on the prefilter are also analyzed. All information is stored in memory.

Accuracy
The accuracy is ±10%.

Advantages
It is usable over a wide ambient temperature and humidity range. No field calibration or training is required.

New technology/developments
A humidity sensor has been incorporated to monitor the relative humidity level of the prefiltered ambient air.

Cost
Approximately $35,000.

RADON DAUGHTER ANALYZER (ACTIVE)

Measurement and analysis
The analyzer contains a filter for the incoming sample air. A computer that plugs into the analyzer automatically computes the radium concentration. Sample air is drawn through a filter for 2 minutes while alpha and beta particle backgrounds are measured simultaneously. The sample deposit on the filter is transported to the detector where all counts are registered for 2 minutes.

Accuracy
Not available.

Advantages

The instrument is usable over a wide range of ambient temperatures and humidity levels do not affect its operation. No warmup time is required. Radium levels are automatically calculated. No training is required for sampling.

Limitations

Periodic maintenance is required.

New technology/developments

None.

Cost

$17,000.

RADON TRACK DETECTOR (PASSIVE)

Measurement and analysis

The passive radon track detector is a card of negligible weight that integrates radon exposure. Alpha particles from radon in the air penetrate the detector and cause damage tracks. The tracks are chemically etched at the end of the exposure interval and counted. Average exposure is proportional to the counted tracks per unit area.

Accuracy

The accuracy is ±1–3%.

Advantages

The instrument is usable over a wide range of ambient temperatures and humidities. It provides good reproducibility. No calibration or maintenance is required, and it is simple to use. No training is required for sampling.

New technology/developments

None.

Cost

$16 to $66 depending upon lot size and sensitivity required.

SULFUR DIOXIDE (SO_2) ANALYZER I (ACTIVE)

Measurement and analysis

This instrument contains a sensing electrode that generates an electric current through an electrochemical reaction. The analyzer has three measuring ranges and can provide a continuous sampling rate. Audible and visual alarms are optional features.

Accuracy

The accuracy is ±2% of full scale.

Features

Requires three different types of battery (total of 7 units).

New technology/developments

None.

Cost

$1700 to $1900, depending upon the model.

SULFUR DIOXIDE (SO_2) ANALYZER II (ACTIVE)

Measurement and analysis

The unit contains an electrochemical cell, a digitizer, and a separate data reader. SO_2 diffuses into an electrochemical cell that produces a signal proportional to SO_2 concentration. The signal is digitized and stored.

Accuracy

Accuracy is ±2% of reading plus one least significant digit.

Advantages

This analyzer uses one long-life 9V battery. It is usable over a wide humidity range.

Limitations

The instrument requires maintenance.

New technology/developments

The latest model features an LCD display instead of data logging.

Cost

$1100 to $1200.

SULFUR DIOXIDE (SO_2) ANALYZER III (ACTIVE)

Measurement and analysis

The analyzer samples 250 mL/min continuously. Sample air is drawn through distilled water. The absorbed sample reacts with pararosaniline

and formaldehyde to form a pararosaniline methyl sulfuric acid. The intensity of this acid is measured in the yellow spectrum.

Accuracy
Not available.

Advantages
No training is required for sampling.

Limitations
Monthly maintenance is required.

New technology/developments
None.

Cost
\$5700 with optional accessory.

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